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An Interdisciplinary Assessment of Biogas Production and the Bioenergy Potential within the South West of England

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**AN INTERDISCIPLINARY ASSESSMENT OF BIOGAS
PRODUCTION AND THE BIOENERGY POTENTIAL WITHIN
THE SOUTH WEST OF ENGLAND**

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A thesis submitted for the degree of Doctor of Philosophy

University of Bath
Department of Mechanical Engineering
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ABSTRACT

There is a growing need to reduce the use of fossil fuels for energy. A twofold reason exists for this: firstly these resources are finite; secondly the utilisation of these resources releases greenhouse gases which are known to contribute towards climate change. The rise in global population and energy use per person is adding to the unsustainable use of fossil fuels.

There is the potential to reduce fossil fuel consumption in the South West of England. The region's abundant natural resources could be used to reduce the overreliance on energy from fossil fuels. A key natural and renewable resource within the region is the availability of biomass. Bioenergy is a form of energy, derived from biomass.

Bioenergy has the capability to displace the use of fossil fuels. Additionally, it has the potential to reduce the effect of climate change by absorbing carbon dioxide during the biomass production period. It has the possibility of being integrated into existing infrastructure and is one of the few renewable technologies which can satisfy an array of end-use energy requirements. This thesis highlights a unique method of assessing the potential of bioenergy in the South West of England using a multi appraisal technique.

The initial assessment within this thesis has examined the resource availability of bioenergy based on biomass feedstock. Whilst quantifying the overall availability, constraints have been examined to determine the realisable potential of biomass as an energy source. The analysis has then assessed the drivers and barriers of bioenergy development within the region and contextualised this for the UK in general. Following the selection of a single bioenergy pathway (biogas production from anaerobic digestion), the technology has been assessed using a multi appraisal methodology. This methodology has involved the use of net-energy analysis, environmental life cycle assessment and financial investment assessments.

The thesis demonstrates that the region has a notable resource availability of biomass. However, a number of barriers to development have been found which could impede the utilisation of this energy source. The selected bioenergy pathway of biogas from anaerobic digestion was found to eliminate some of these barriers. Assessing the potential of biogas using multi appraisal techniques highlighted that this pathway could, in some cases, offer positive environmental, energy and financial benefits.

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GLOSSARY

AD (Anaerobic Digester) – This is the biological reaction for biogas production. The biogas is produced within an *anaerobic digester*.

Biogas – The by-product of AD. The gas is a mixture of methane, carbon dioxide and trace elements. It can be highly flammable.

CV (Calorific Value) – The amount of heat evolved when a unit mass of a fuel is burned completely under standard conditions.

CHP (Combined Heat and Power) - A method of recuperating waste heat from electricity generation.

Discount Rate – Is the conversion factor by which money is valued at different points in time and related to a single point in time.

ERE (Energy requirement for Energy) – The sum of all primary or resource energy dissipated to give one unit of delivered energy (delivered means and end-user energy such as electricity or diesel fuel).

FIA (Financial Investment Appraisal) – The technique for assessing the financial feasibility of an investment, taking into account annual revenue, expenditures and capital costs.

GCV (Gross Calorific Value) – The amount of heat evolved when the products of combustion are cooled to ambient conditions (25°C) and water vapour has condensed, evolving its latent heat.

GER (Gross Energy Requirement) - The sum of all the primary (or resource) energy sources, expressed in terms of heat that must be dissipated in order to produce a good or a service.

LCA (Life Cycle Assessment) – A procedure of study for determining the environmental impacts of a product or a process.

Met Office - An abbreviation for 'Meteorological Office', but now the official name of the UK national weather service.

MC (Moisture Content) – The specific water concentration within organic matter. This is often represented as a volume percentage.

NCV (Net Calorific Value) – This is a measure of the heat evolved when the products of combustion are cooled to ambient conditions and the latent heat of condensing water is deducted.

Primary Energy – Energy that is extracted from natural resources and not subjected to any conversion processes.

PV (Present Value) – The current monetary value arising at a future date; this is found by applying a *discount rate*.

SEDBUK - Seasonal Efficiency of Boilers in the UK.

TS (Total Solids) – A measure of the dry matter within an organic substance. This is related to the MC.

VS (Volatile Solids) – A measure of the active (or volatile) fraction within the TS of an organic material.

1 INTRODUCTION

1.1 *Energy within a global society*

Human development requires energy. Energy is essential for many aspects of life and the demand for energy continuously grows. Globally, this increase in demand is a result of two factors. Firstly, the energy requirement per person has increased. Secondly, there is a growing population of energy consumers. The United Nations predict that by 2050 the earth's population will be around 9 billion people, an approximate 30% increase on current times (Kilbert 2005).

Energy cannot be created or destroyed. It can only be converted from one form to another. Ultimately, all energy on earth is derived from the sun. The solar energy received on earth is approximately 11,000 times the global energy demand per year (Ecofys 2005). Due to the high dispersion, only a small amount can be recovered for energy purposes.

Fossilised resources (fossil fuels) are the most common energy source converted to utilisable forms such as liquid (oil), gas and solid (coal). They have amongst the greatest energy per unit volume or energy density and are relatively easy to obtain and convert into utilisable energy. Fossil fuels used for energy conversion became significant during the 19th century through the heavy use of coal. On improving the conversion efficiencies, the power of oil became apparent and oil and gas began to substitute the use of coal. Since then the world has been heavily reliant on fossil fuels (Ecofys 2005).

Fossil fuels are recognized as non-renewable sources of energy; signifying they cannot be renewed on a timescale which can sustain their consumption. Due to this fact, fossil fuel depletion occurs faster than the rate at which they can be created. This would not be problematic if there was an infinite supply of fossilised resources within the earth's crust. However, the resource of fossil fuels are globally believed and accepted to be finite and fossil fuel discoveries are becoming too costly in monetary or energy terms to be utilisable (Longwell 2002).

1.1.1 **Historical energy use**

The demand for energy has increased dramatically over the past 100-150 years and is predicted to increase further. Currently, most of the energy demand is met by burning fossil fuels (Deublein & Steinhauser 2008). As global energy consumption has increased, so too has the use of crude oil, natural gas and coal. The two graphs show how primary energy consumption has increased (see Figure 1-1 and Figure 1-2).

Between 2005 and 2030, the energy demand is predicted to increase by 50% (EIA 2008). Nineteen percent will arise from OECD¹ countries whilst over 80% of this increase will come from non-OECD countries (EIA 2008). Therefore, the reliance on oil, natural gas and coal will increase. Oil production has been closely monitored over the past 50 years by a number of organizations. These established sources record and publish annual global oil consumption figures (BP 2008;EIA 2008;ENI 2008). These have been displayed in Figure 1-1.

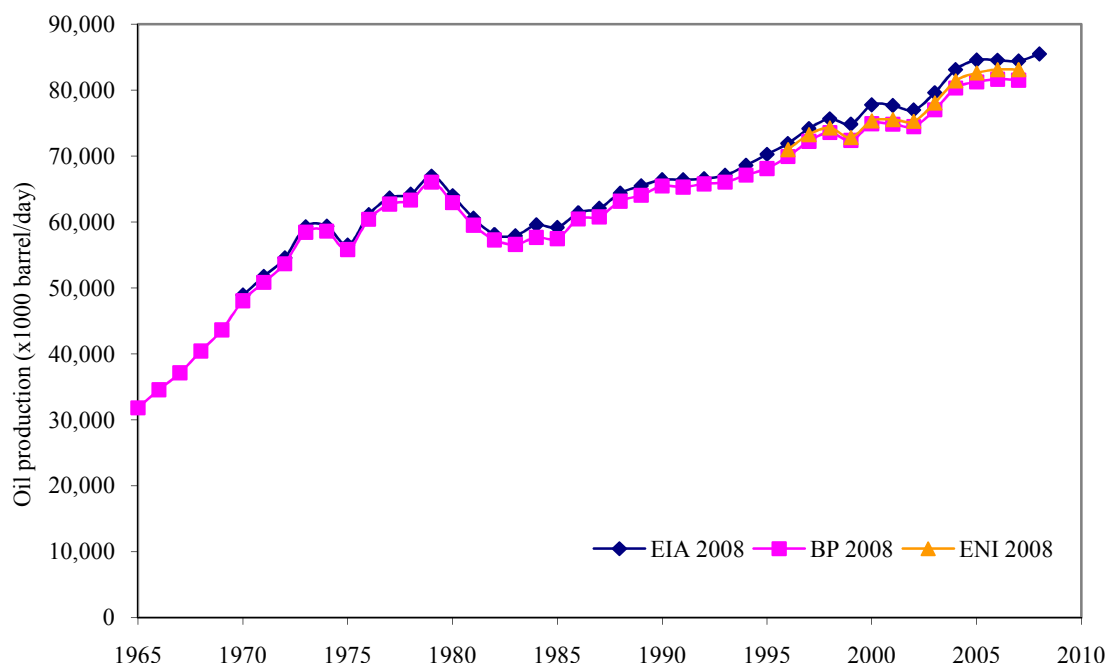


Figure 1-1 Global oil production (thousands of barrels per day). Source: (BP 2008;EIA 2008;ENI 2008)

Global oil production has steadily increased over the past 50 years and is predicted to increase significantly over the next 40 years (EIA 2008). According to some sources, the proven oil reserves could supply global oil demand for the next 40 years and show that global reserves have increased at a similar rate to oil consumption/production (BP 2008). However, other sources (Longwell 2002) suggest that oil discoveries are significantly lower than predicted and publicised. According to one of the largest global oil suppliers, the average size of oil fields found from 1950 to 2000 have dropped to 20% of original findings (Tsoskounoglou et al. 2008). Tsoskounoglou et al. (2008) stated that global oil discoveries peaked during the 1960s and since then discoveries in volumes of oil have reduced (*ibid*). Therefore the rate of new oil reserve discoveries has not expanded at the same rate as global production, indicating that oil is being consumed at an unsustainable rate. The discrepancies in the literature make estimating the remaining oil reserves difficult.

¹ Organisation for Economic Co-operation and Development (OECD) member states are countries that represent the principles representative democracy and accept free-market economy. These tend to be developed countries with relatively high GDP/person. Currently only 30 countries are OECD members.

Global energy resources are often associated with fossilised oil, natural gas and coal, due to the commanding share that these energy sources have over alternatives such as nuclear and renewable energy. In 2005, 34% of the global energy demand was met by oil, 26% from coal and 22% from natural gas (EIA 2008). This equates to 82% of the global energy demand, with the remaining 18% being supplied by nuclear and renewable energy sources.

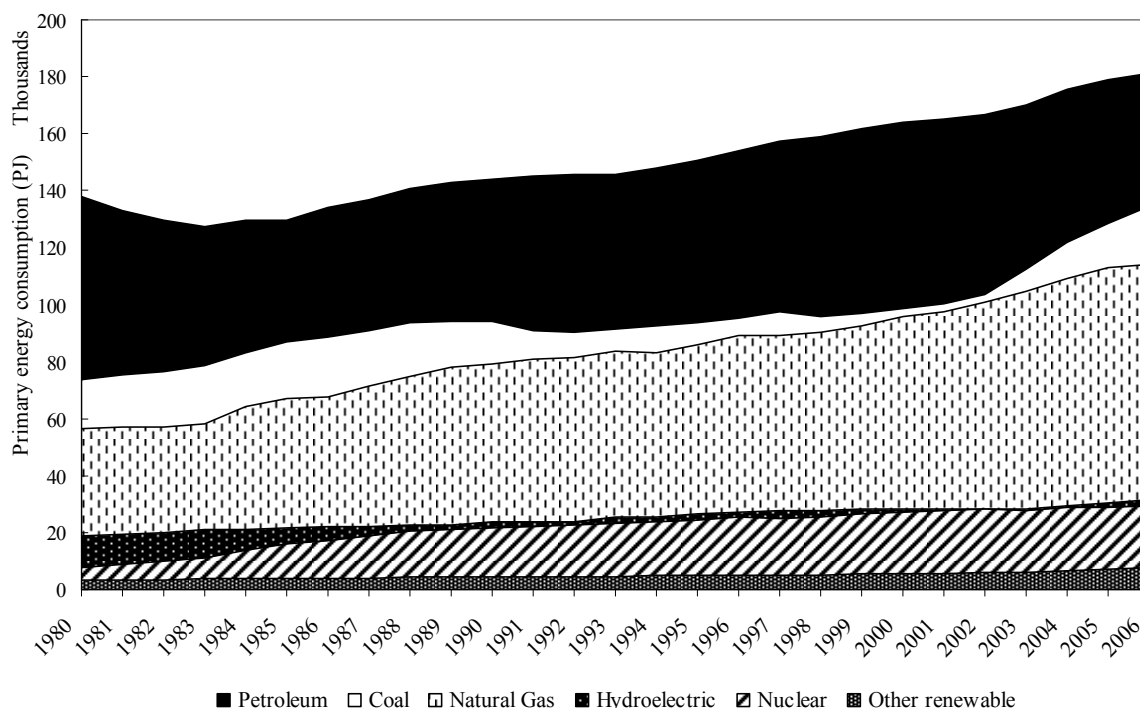


Figure 1-2 Historical global energy use by resource (International Energy Agency 2006)

Energy conversion through fossilised resources releases the carbon stored internally within the material. On release into the atmosphere it generates a carbonic gas bonded with oxygen, called carbon dioxide (CO₂). Carbon dioxide is recognised as being a greenhouse gas (GHG). This gas has the potential to create a change in the earth's climate; called the greenhouse effect. An increase in GHG in the atmosphere changes the balance of solar radiation received and rejected from the earth. This is caused by blocking the solar radiation within the earth's atmosphere, consequently altering the climate (IPCC 2007b).

This effect on the earth's climate (climate change) is believed to be a natural phenomenon possibly contributed towards by human activity; a theory which has been widely recognized by scientists globally. As a result of increasing international concerns regarding climate change, in 1988 the International Panel on Climate Change (IPCC) was instituted to evaluate this risk caused by human activity. Through the IPCC, a number of reports have been released, of which the latest was published in 2007 (IPCC 2007a). The report highlighted that global average surface temperatures had increased steadily, along with global average sea levels whilst northern-hemisphere snow cover had decreased. These trends were found to be especially significant from 1950 to present time (IPCC 2007a).

Following the launch of the IPCC, the United Nations Framework Convention on Climate Change (UNFCCC) was established to address the issue of climate change globally (United

Nations 2004). This framework is represented by 189 countries highlighting the near global participation in tackling climate change. Adopted in 1997, the Kyoto protocol was implemented ensuring countries (of which 184 signed the agreement) had to meet reduced targets of six primary GHGs (carbon dioxide, methane, nitrous oxide, sulphur hexafluoride, hydro fluorocarbons and per fluorocarbons) (United Nations 2008). Carbon dioxide is considered the most critical greenhouse gas as this represents 77% of the total global GHG emissions and has risen by 80% during 1970-2004 (IPCC 2007a). The largest contribution to these emissions is believed to be the conversion of fossil fuels into energy supplies.

The need to reduce the global dependency on fossil fuel resources is apparent. This requirement is not based solely on the depletion of finite resources, but also the need to reduce the possibility of affecting the global climate. The need for change, recognized globally, must be initiated on a national level.

1.1.2 Energy use in the UK

The UK's energy position is similar to that of the global representation. Energy consumption in the UK has grown steadily and since 2004 the UK has become a net-importer of fuel (BERR 2008a). In fact, the UK has a higher reliance on fossil fuel energy than the global average (92% as opposed to 82% of total energy supply met by fossil fuels). In 2007 the UK required 235 million oil equivalent tonnes (toe) of primary energy (BERR 2008a), of which 18 million toe were from non-fossil resources.

The rate of energy consumption is related to the growing energy demand in the UK. Energy demand in the UK can be categorised by end-user. These include: industry, transport, domestic and services. In 2007, the UK transport sector was the most energy intensive (requiring 38.5% of the total UK energy); whilst domestic and industrial energy demand accounted for 28.5% and 20.5% respectively (BERR 2008a). In 1970, nearly half of the UK's energy consumption lay within the industrial sector (42.5%), with domestic energy consumption contributing to 25.5% and transport sector being responsible for 19.5% (*ibid*). The shift in demand was partly caused by a reduction of heavy industry within the UK but also an increase in road transportation over the past 40 years. Energy policy in the UK has been documented through a number of Energy White Papers (BERR 2007a). The most recent white paper highlighted four policy goals for meeting future energy demand. These are as follows (BERR 2007a):

1. To put the UK on a path to cut carbon dioxide emissions by 60% by 2050, with real progress by 2020;
2. To maintain reliable energy supplies and security of energy;
3. To promote competitive energy markets in the UK and beyond, helping to raise the rate of sustainable economic growth and to improve productivity;
4. To ensure that every home is adequately and affordably heated.

The Kyoto protocol committed the UK to reduce the country's GHG emissions by 12.5% during 2008 to 2012, based on 1990 levels. Furthermore, the UK launched its own Climate Change Programme in 2000. The programme aimed to adhere and surpass the requirements set by the Kyoto Protocol and introduced a new target of 20% (23-25% GHG emissions) reduction in CO₂ emissions from 1990 levels, by 2010 (HM Government 2006).

In response to these targets, in November 2008, the UK created the Climate Change Act with the aim to reduce GHG emissions to 80% of 1990 levels, by 2050 (HM Government 2008). Prior to this, the target had been set at 60% following the recommendations from the Royal Commission on Environmental Pollution (RCEP 2000). These recommendations arose from research showing that if countries adopted this target, it would limit CO₂ concentrations to a suitable level to stop rising atmospheric temperatures (around 2°C) (CCC 2008).

In 2008 a report commissioned by the Committee on Climate Change (CCC 2008) stated that the targets set in the RCEP report were based solely on CO₂ levels and failed to consider the other major GHG emissions. Using updated calculations they reported that mean global temperatures would rise considerably more than previously thought by the RCEP. Due to these findings, a new target of 80% GHG reduction from 1990 levels was introduced (HM Government 2008). In order to meet these targets, the use of low carbon technologies could help provide part of the solution. The displacement of conventional carbon emitting energy sources could help reduce CO₂ emissions. Through the decarbonisation of energy supplies, the use of renewable energy is expected to have a significant contribution (CCC 2008).

In 2009, the UK set-out plans to achieve a 15% renewable energy target by 2020 (HM Government 2009). This is primarily to reduce national CO₂ emission levels, but also to help reach the recent legally binding, renewable energy targets set by the European Commission for the UK (European Commission 2009). The aim of the EU targets is to reduce GHG emissions by 2020 in order for its member states to meet the Kyoto Protocol targets. To do this, they envisage an increase in renewable energy use across Europe. Despite the initiative, the renewable energy target for the UK is amongst the lowest of the 27 EU member states (House of Lords 2008).

The UK Government strategy suggests that 30% of electricity, 12% of heat supply and 10% of transport energy consumption is obtained from renewable resources (HM Government 2009). To do this, the UK has at its disposal a number of renewable energy sources including wind energy, solar, hydro and biomass (HM Government 2009).

1.2 Aim and scope of work

As the role of renewable energy is set to increase in the UK, energy from biomass (bioenergy) is considered to have a crucial role in meeting Government-set targets (BERR 2007b; HM Government 2009). The range of end-uses for bioenergy enables it to be used for electricity production, heat generation and transport fuel. This makes it one of the few renewable energy sources which can contribute towards the whole spectrum of energy demand in the UK. This source of energy could potentially contribute to lowering CO₂ emissions within the three energy demand sectors, highlighted earlier. The flexibility of bioenergy and the range of applicable biomass resources available advocate the necessity to quantify and understand the true potential of bioenergy in the UK.

The implementation of biomass technologies within the current energy mix could not only reduce carbon emissions but also improve energy security if fuels were sourced and produced locally. However, the use of biomass for energy purposes has raised growing concerns over the past years. Biomass production may result in a reduction of food availability and cause

other environmental issues with unknown results, such as expansion of monocultures (The Royal Society 2008;WWF 2007). In some cases, the use of bioenergy may only offer little, if any, carbon savings when the whole life cycle of some bioenergy pathways are considered (Pool 2007).

In 2005, the UK Government commissioned the Biomass Task Force (Gill et al. 2005) to identify pathways for delivering bioenergy in the UK. The task force identified a lack of mature and robust supply chains in bioenergy, a general lack of knowledge of bioenergy and a lack of strong market signals for its requirement. The report created a number of recommendations in order to develop the use of bioenergy in the UK (*ibid*). In 2007 the Government produced the UK Biomass Strategy as an obligation in response to the task force (BERR 2007b). The strategy addressed the Government's vision for bioenergy use and development in the UK, stating that bioenergy could be enhanced by:

- Sourcing an additional 1 million oven-dry tonnes (ODT) of wood per annum in England by developing currently unmanaged woodland and increasing the recovery of wood from managed woodland;
- Increasing perennial crop production for biomass in the UK, with the potential to use up to a further 350,000 ha across the UK by 2020 (capable of yielding around 3.5 million ODT of miscanthus per year: assuming a miscanthus yield of 10 ODT/ha per year);
- Increasing the supply and management of organic waste.

Within the UK, the region of the South West of England comprises of Bristol, Gloucestershire, Somerset, Dorset, Wiltshire, Devon and Cornwall. The region has preferential conditions for bioenergy production. These include generally higher climatic temperatures and rainfall than the rest of the British Isles, optimal for biomass growth (McKendry 2002a). The South West's large agricultural land area, comprising over 80% of the total available land, makes it an attractive location for energy crop production. Extensive farming raises the potential for a high supply of organic waste suitable for producing biogas. Managed woodland accounts for around 43% of total woodland in the region which has the potential for an increase in woodfuel (Hammond et al. 2008a).

The regional benefits for bioenergy use have been highlighted in a number of regional strategies and policies (O'Rourke 2001;RegenSW 2003). This was also supported by the Regional Economic Strategy for the South West of England 2006 – 2015 (SWRDA 2006). This source outlined the need to drive the economy forward by the development of alternative fuels in light of climate change. It also stated that the South West Region had the capacity to become a world leader in renewable energy, although recognising that the natural environment is a fragile resource that needs protection (*ibid*). Due to the region's strong potential from natural and renewable resources, renewable electricity targets have been set higher than the national average (of 2006) at 11–15% by 2010 (RegenSW 2003).

It is evident that there is a need to examine accurately the potential of bioenergy within the South West of England. The overall aim of this research is to examine the role of bioenergy within this region. This will be done based on biomass resource availability, bioenergy

pathway applicability² and environmental and financial implications. Additionally, an understanding of the prospects and barriers faced by the development of bioenergy in the South West of England will also be examined. These research aims and objectives require an interdisciplinary approach. The integration of diverse disciplines will become apparent when addressing the project objectives.

The research is divided into a number of key sections (research questions). The study questions have been listed and detailed within the following sections.

Research Topic 1 - What is the bioenergy resource potential of the South West?

The aim of this section was to determine the current use of bioenergy within the region and contrast this with the potential availability of bioenergy resources. An analysis of the South West's resources was required, along with an assessment of the region's energy use and potential energy pathways. Bioenergy is considered an umbrella term for a large family of biomass-to-energy pathways. Therefore this research enabled an understanding of which pathway or pathways could be more favourable for the region, in terms of resource availability. Identification of the biomass resources currently and potentially available in the region was made and contrasted with earlier renewable energy assessments for the region.

Research Topic 2 - What barriers are placed on the development of bioenergy in the South West?

This study determined the technical and other constraints inhibiting the exploitation of bioenergy in the region via case studies of recent real-life projects. The analysis was subsequently expanded to represent the bioenergy drivers and barriers for the UK as a whole. Following an assessment of failed or non-initiated bioenergy projects in the South West a stakeholder survey determined the main barriers and drivers to bioenergy development in the region. Documentation and analysis of the results then followed.

In agreement with the UKERC, the study subsequently focused on a single bioenergy pathway, biogas from anaerobic digestion. This resulted from the findings of the first research question 'What is the bioenergy resource potential for the South West of England'.

Research Topic 3 - What are the energy benefits of bioenergy (biogas) development?

The energy analysis addressed the efficiency of the process and examined the net-energy benefits (or detriments). It also represented energy requirements for energy and the fossilised resource requirements for biogas production. From the study it was possible to determine the fossil resource avoidance gained by adopting this technology for electricity production, heat or transport energy.

² Throughout the thesis, a bioenergy pathway is defined as the type of conversion process from biomass feedstock (raw form) into a utilisable energy form (bioenergy).

Research Topic 4 - What are the environmental impacts attributable to bioenergy (biogas) development?

The second part of the energy and environmental impact study was to evaluate the environmental impacts of biogas production and its processes. This was done by undertaking a full life cycle assessment (LCA) from cradle to grave. The environmental impacts of making and using biogas were then reported. From this investigation, the effects of adopting biogas energy for the South West of England were discussed, determining whether biogas would have positive or detrimental impacts upon the environment.

Research Topic 5 - What are the financial implications of adopting bioenergy (biogas production and use)?

Specific biogas plants in the UK and Europe were studied so that a financial investment appraisal for biogas could be developed. This was then applied to the region, highlighting the costs associated with exploiting biogas. Due to the versatility of biogas, a cost comparison between different uses was also made. An assessment of the quality of inputted data was carried out using a sensitivity analysis.

1.3 Documenting the research

The environmental impact assessment, financial investment appraisal and energy analysis formed the basis of the multi appraisal technique. The methodology for this appraisal technique has been addressed in Chapter 5. The results from these analyses were then discussed within the context of the South West of England. Contextualizing the results in this way enabled the studies to be interlinked and cross-referenced throughout the thesis. The results from the resource assessment study were presented at the 2008 UKERC Annual Assembly. The work was then selected for publication in the special issue of the ICE Journal 'Energy research in context' (Hammond et al. 2008a). The results from the study on barriers and drivers for bioenergy were also presented at the 2008 Biomass and Energy Crops III conference in December 2008.

1.4 Thesis structure

The structure of the thesis focuses primarily around the research questions set out at the initial stages of the research. The thesis is divided into eleven chapters, with the core UKERC research questions addressed between Chapters 3-9. The first two chapters present the reader with an overview of energy use and production, followed by a review of bioenergy pathways. The chapters responding to the specific research questions discuss the findings and are assessed from a regional perspective. Conclusions, recommendations and further work are then addressed in the final chapter, highlighting the author's final thoughts. The structure has been represented in Figure 1-3.

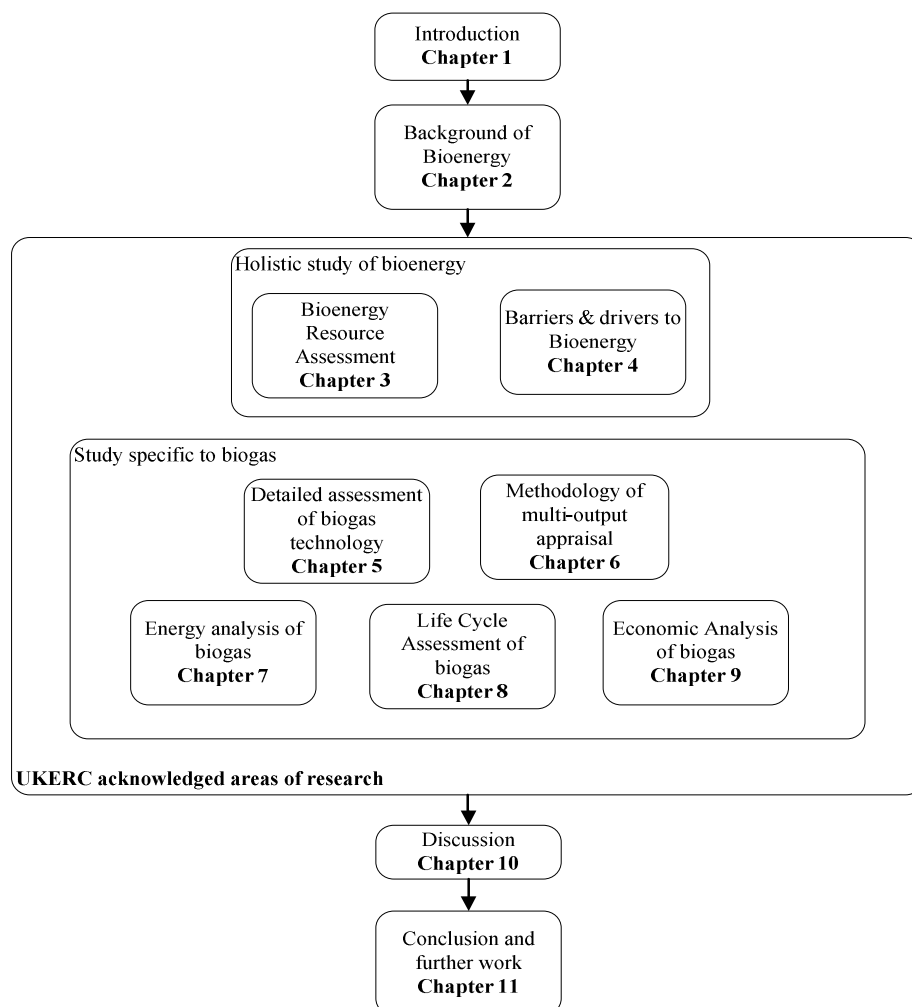


Figure 1-3 Thesis and research structure

2 BACKGROUND TO BIOENERGY

Energy from biomass (bioenergy) is considered a viable option for sourcing energy from renewable sources. This chapter details the fundamentals of biomass and its transformation into a useable energy source. A critical analysis of bioenergy pathways has also been carried out examining the potential of each bioenergy process.

Throughout this thesis the following terminology will be used (shown in Figure 2-1): biomass is a source of feedstock and can be any type of organic matter. Biofuel, biogas or bio-solid is the fuel form obtained after processing or preparation. Finally, bioenergy is a measure of the energy capability of the biomass.

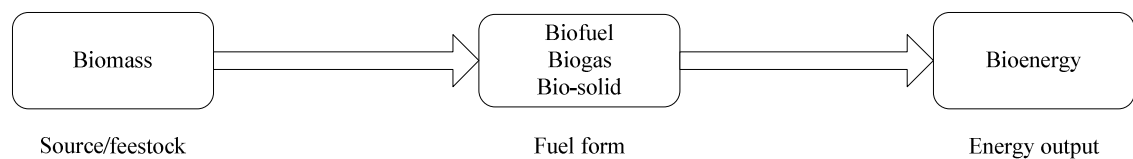


Figure 2-1 Bioenergy supply chain. Adapted from FAO (2004)

Biomass is defined as living or recently living organic matter (White & Plaskett 1981). All organic matter is essentially derived (directly or indirectly) from photosynthesis, converting energy from the sun into chemical energy stored within organic material. Energy that can subsequently be derived from biomass and used for societal energy requirements is called bioenergy.

Biomass from plants originates from the sun's captured energy radiation. In addition to the sun's radiation, carbon dioxide is also absorbed and converted into sugar and starch. The photosynthesis process also creates oxygen, essential for humans and animals to survive. The photosynthesis cycle in biomass can be displayed in a simplified equation as shown:



The potential for energy recovery from biomass signifies that biomass is a good energy carrier (from the sun's energy to useful energy for society). This makes energy from biomass an attractive source of "free" energy, as it does not rely on fossil-based resources. The conversion of the sun's energy into biomass energy is however, very inefficient. For example, solar energy intensity in England is approximately 33,000 GJ/ha/yr (White & Plaskett 1981). With a UK land covering of around 13 million ha, this equates to a total received solar energy of around 430,300 TJ/year (roughly equal to 120 million GWh/year). Assuming a total primary energy use in England of around 5,000 TJ; the solar radiation could provide more than 86 times the country's energy demand. Although the availability of energy is high, the utilisable energy from the sun becomes very low through a number of inefficiencies.

The theory above shows that photosynthesis is an ineffective method of converting the sun's energy into utilisable biomass. The average conversion efficiency is between 1-2% (Slessor & Lewis 1979). This is a result of a number of factors which ultimately reduce the "useful energy" received from the sun. The efficiency is affected by the climatic conditions experienced by the biomass during the growing stage. For example maize (C₄) grown in the

USA has a photosynthetic efficiency of 0.5%, whilst in Japan the efficiency rises to 1.1%. This ultimately results in a change of annual yield over dry tonne (ODT) production of 10 ODT/ha/yr (Cooper 1975). Although crop yields will have increased since this source was published, the relationship still holds true. This change is brought about by climate and other factors; however it is generally considered that areas at low altitudes with a low occurrence of chilling temperatures produce higher biomass yields (Slesser & Lewis 1979). As a result the actual utilizable energy from biomass is significantly lower than the received, non-reflected, energy from the sun. Consequently biomass production requires large areas of land.

Once the biomass has been produced it contains the internal energy which through a series of processes can be extracted and used. One of the most common energy extraction processes of biomass is direct combustion. The combustion of dry biomass releases energy in the form of heat up to and over 400°C in some cases (Twidell & Weir 2006). During this combustion, the embodied carbon is converted into carbon dioxide (CO₂) which is then released into the atmosphere. As biomass production requires the absorption of CO₂, the overall process can be considered as carbon neutral and commonly known as the carbon cycle.

A schematic of the carbon cycle has been shown in Figure 2-2. The cycle is a closed loop resulting in all the carbon emitted from biomass combustion being re-collected through photosynthesis. Although this cycle is known as carbon neutral, some energy is required to obtain energy from biomass. Therefore, this prevents the system from being completely carbon neutral.

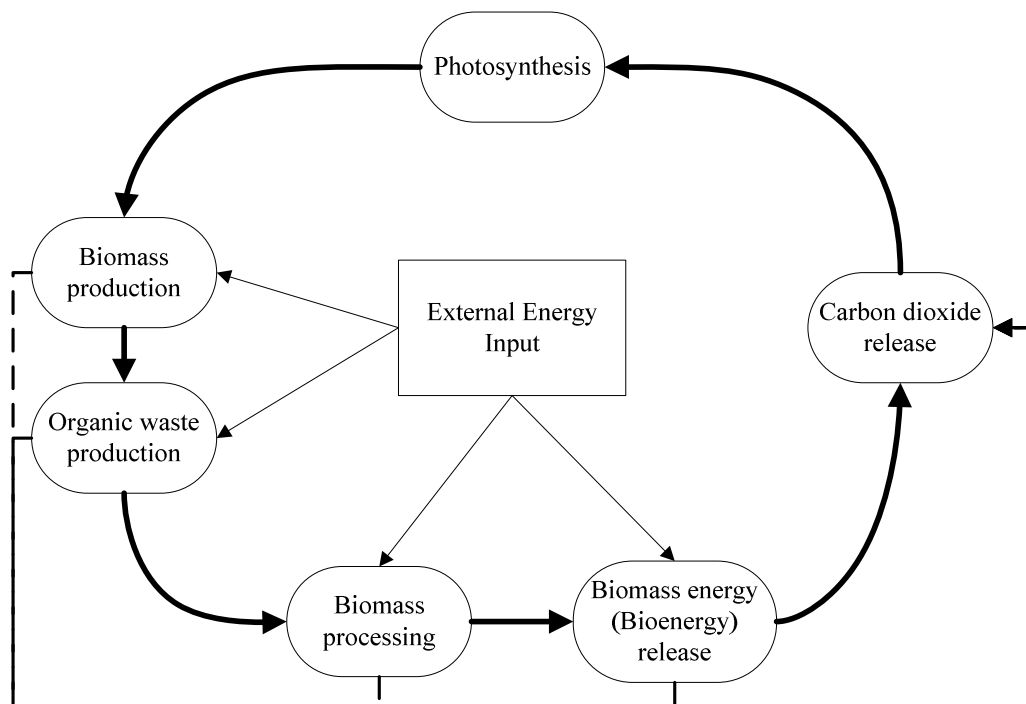


Figure 2-2 Carbon cycle for biomass with carbon emitting factors for fuel production

Within the bioenergy supply chain there are four key areas where 'external' energy is required and subsequently CO₂ is released. These consist of growing and collecting the biomass feedstock, processing the biomass into a utilisable energy source and transporting the bioenergy to its required destination. The energy required during these stages is in the form of diesel for transport and fossil fuel combustion for electricity and heat intensive processes.

These processes subsequently emit carbon dioxide thereby adding to the emissions associated with the bioenergy.

At present bioenergy is commonly assumed to have external energy inputs derived from fossil fuel sources. However, if bioenergy were developed on a larger scale in a sustainable method, then these external energy sources could be derived from bioenergy itself. For example, biodiesel could be used for transportation and bioenergy from biogas or biomass combustion could supply heat and power generation. Consequently the biomass carbon cycle would be closed as no fossilised energy sources would be needed. If this approach were undertaken, the energy output of bioenergy per unit input of bioenergy would be significantly reduced. A unit MJ of bioenergy would require a greater amount of biomass. This could impact upon a number of environmental factors, including land-use and resource availability.

2.1 *Types of biomass*

A detailed description classifying and describing biomass types has been illustrated in Chapter 3. However, biomass resources can be classified into four groups. These include:

- Arable/annual crops;
- Herbaceous perennials;
- Woody perennials;
- Residues and waste.

However, there are other sources of biomass, such as aquatic biomass which do not directly fit into these four categories. These categories cover the more commonly used biomass feedstocks.

Biomass plantations are defined either as perennial or annual. Annual plants have a one-year lifecycle from seed plantation to growth to seed plantation again. Perennial plants have a longer lifecycle (above 2 years). Perennials can include grasses, such as miscanthus and switchgrass and woody plantations such as short rotation coppice, pine or spruce. Plants which have no ligneous content above ground are defined as herbaceous. These plants can either be annual or perennial. Herbaceous plants can also be classified as high or low moisture content (McKendry 2002a), which subsequently determines the use of the biomass. Residues and wastes include all farming manures and any type of organic derived waste.

The type of energy desired and the conversion processes available often determines the type of biomass feedstock used. However, some sources of naturally occurring biomass (or part of the waste cycle of other systems) will often dictate the type of energy that can be supplied rather than the type of energy desired, as is often more preferable.

2.2 *Bioenergy conversion processes*

Energy housed within biomass can be stored for long periods and can then be extracted through a series of techniques, shown in Figure 2-3. These techniques convert the energy from within the biomass into utilizable form. This process is commonly referred to as bioenergy conversion process.

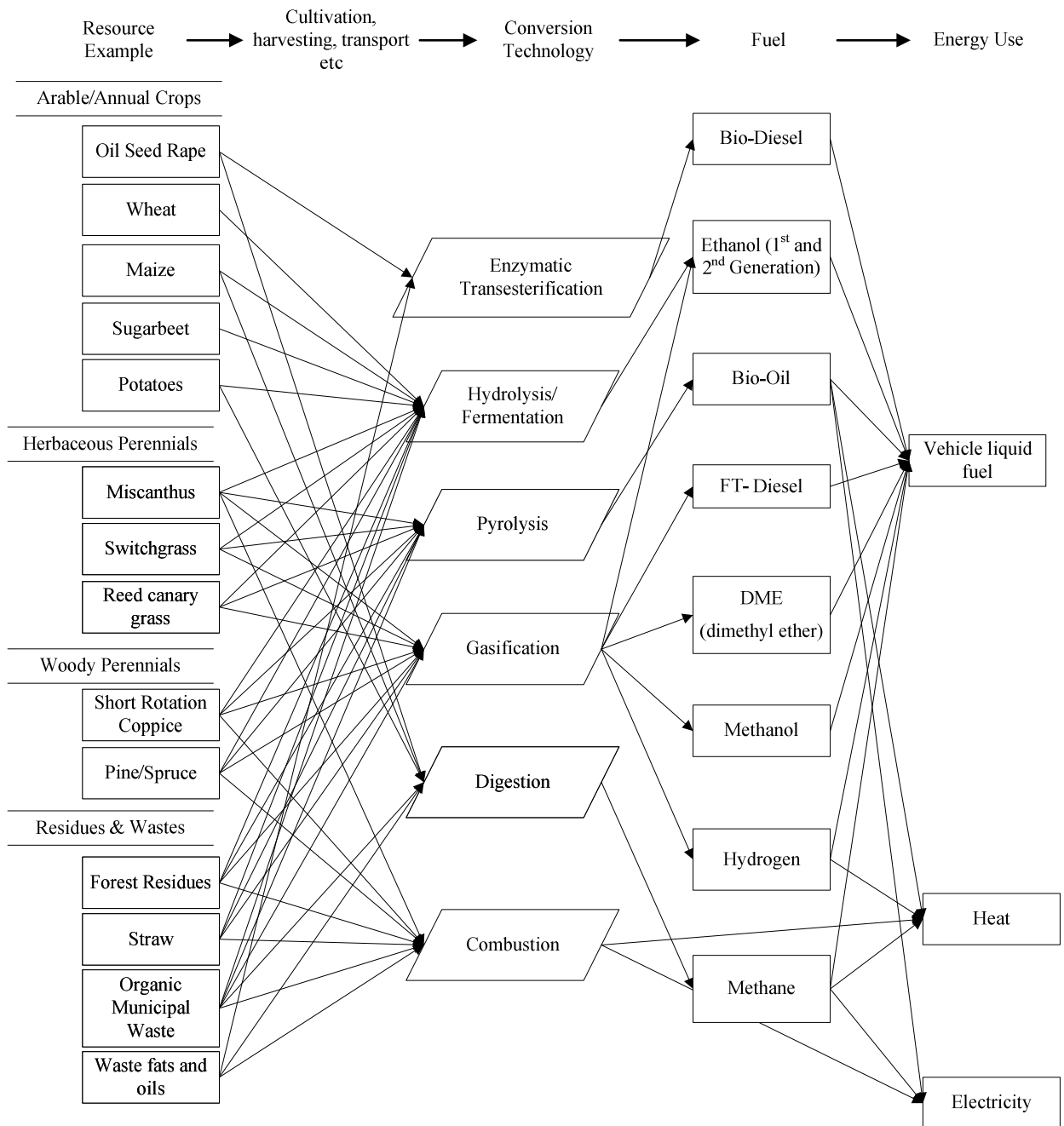


Figure 2-3 Bioenergy pathways. Adapted from Hammond et al. (2008b)

Conversion processes for biomass to energy have been established and documented through the literature (FAO 2004; Hammond et al. 2008b; McKendry 2002a; McKendry 2002b). The process flow chart in Figure 2-3 shows an overview of the major bioenergy pathways. Generally conversion techniques can be grouped into three types: thermo-chemical, bio-chemical/biological and physio-chemical conversion (McKendry 2002a). Thermo-chemical conversions include combustion, pyrolysis and gasification. Bio-chemical processes include fermentation and anaerobic digestion. Thirdly, physio-chemical conversion processes convert crops into liquid forms of bioenergy through processes such as esterification.

Biomass for bioenergy production can be categorised as primary or secondary resources. Primary biomass resource is an organic material that can be used immediately in its organic

form, such as wood for combustion. Secondary biomass resources are obtained in the form of bio-solid, biofuels and biogases and are available subsequent to a conversion process (FAO 2004). Bioenergy conversion techniques vary depending on resource availability, conversion technology adopted and end-use requirements. Conversion processes available for biomass result in a range of bioenergy fuels and subsequent energy uses. The most common conversion processes have been described in detail within the following sections.

2.2.1 Thermo-chemical conversion processes

Gasification – This is a high temperature conversion process (over 600°C). Biomass is subjected to an elevated temperature with limited supply of oxygen. The lack of oxygen in the combustion process leads to an energy gas (syngas). A lower calorific value of gas would be obtained with air only, which is due to the dilution by the nitrogen. The product gas (a mixture of carbon monoxide, carbon dioxide, hydrogen and methane) can then be combusted for heat or electricity production. Feedstocks for this process include herbaceous perennial grasses, woody perennials, residues and waste. The remaining residue is biochar, which can be used as a fertilizer. The typical calorific value of the product gas is between 4-8 MJ/m³ (Schuck 2006). This is relatively low compared to natural gas or other biogas compositions. The process has been shown schematically in Figure 2-4.

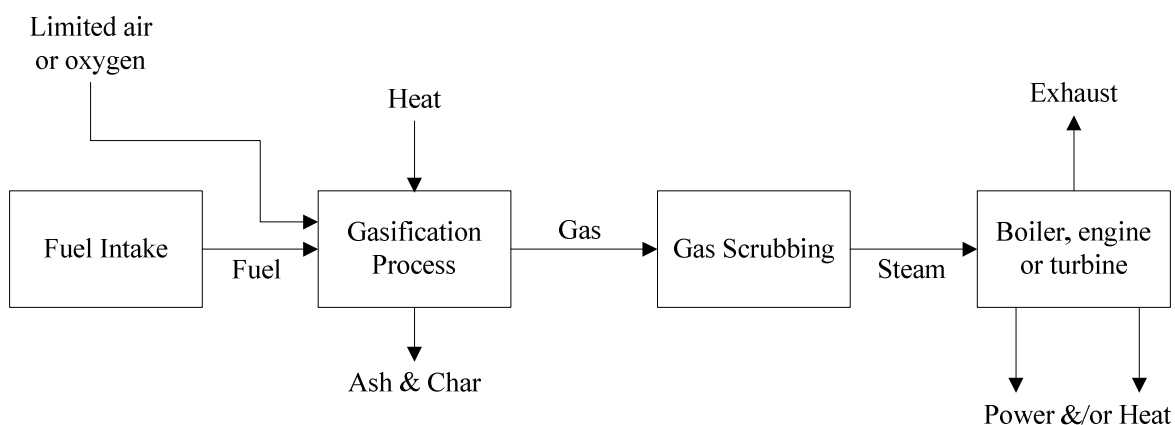


Figure 2-4 Gasification process flow. Adapted from Schuck (2006)

The production of gas from this process offers an attractive proposition over existing standard combustion processes as it results in a wider range of uses for the biomass. Additionally, the temperatures achieved from gaseous combustion can be considerably higher than combustion of some solid biomass. Although a relatively under-utilized technology with commercial uncertainties, this technology was used in Germany during the 1930-40s for the gasification of wood. However the abundance of financially attractive oil has resulted in slow growth of this technology (Ecofys 2005).

Pyrolysis – Similarly to gasification, this is a high temperature conversion process reliant on the removal of oxygen. Biomass is subjected to high temperatures in the absence of air. During the process, the residue produced is carbon. Feedstocks for this process include herbaceous perennial grasses, woody perennials, residues and waste (Schuck 2006).

Pyrolysis produces a wide range of combustible fuels including gases, vapours, liquids and oils. The type of yield is dependant on the operating temperature and the type of material processed. The process efficiency, which is the energy of combustion produced from the secondary fuels divided by the energy of combustion of the input biomass, is between 80-90% (Twidell & Weir 2006). From one tonne of dry wood converted through pyrolysis, the expected output is as follows: 200 kg of charcoal, 140 m³ of combustible gas, 76 litres of wood oil, and 120 litres of other oils or acids (Twidell & Weir 2006). Although the technology appears to have a promising potential, it is still at demonstration stage and is considered too early and financially unfeasible for commercial implementation (Rosillo-Calle 2006). The schematic of the process has been shown in Figure 2-5.

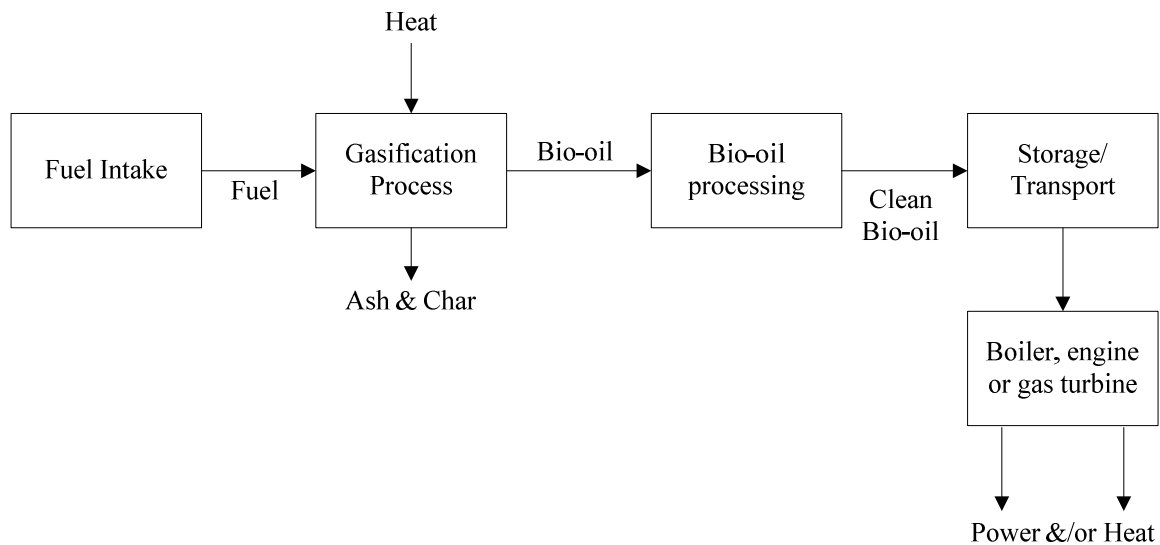


Figure 2-5 Process flow of pyrolysis biomass conversion. Adapted from Schuck (2006)

Combustion – Direct ignition of biomass can be used to recover thermal energy. The thermal energy is generally used as low-grade heat. However it can also be converted into electricity through the production of steam. The process can be fuelled by most biomass feedstocks, provided the moisture content (MC) of the material is less than 50%. The process is 90% efficient for heat production; however this is significantly reduced for electricity production (17-25%) (Rosillo-Calle 2006). Gas cleaning process consists of scrubbers, bag filters and other systems which can reduce air pollutants (Schuck 2006).

This technique can be used within co-firing processes. Co-firing is the addition of biomass to a primary fossil fuel such as coal. Co-firing can provide significant reductions in carbon emissions through its use in large scale applications. However, direct combustion of biomass is regarded as relatively limited compared to other conversion techniques such as gasification, with limited end-uses for the biomass (Figure 2-6).

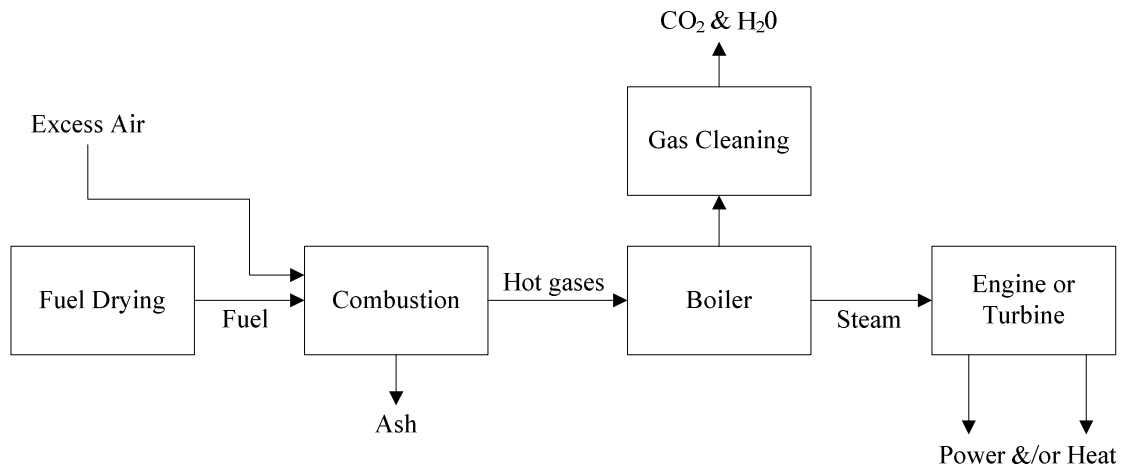


Figure 2-6 Combustion process flow. Adapted from Schuck (2006)

2.2.2 Bio-chemical conversion processes

Fermentation – This process is the conversion of carbohydrates into alcohols or acids through a biochemical process. The process is usually carried out under anaerobic conditions; however, this can vary depending on the feedstock. Most types of biomass feedstocks can be used for fermentation processes, provided sugars such as glucose, fructose and sucrose are present. The most common type of fermentation process is the production of bioethanol from sugar or starch crops.

Ethanol production is effectively alcohol production and therefore the process is well established and in some cases efficient. The use of this liquid fuel can be integrated into existing internal combustion engines (ICE) and used as a transport fuel. However there are small modifications required in order to make this operable (such as modifying the ignition timing). Ethanol can be used in unmodified engines up to a 10-15% blend, denoted as E10 or E15 (Twidell & Weir 2006). The process has varying efficiencies based on the scale of the plant and the type of feedstock used. For example, ethanol yields can vary by over 500% depending on the type of crop used (sugarcane = 70 litres per tonne of crop, maize = 370 litres per tonne of crop) (*ibid*).

Hydrolysis and fermentation – This involves a chemical reaction which converts raw feedstock cellulose chains into glucose. These can then be fermented for bioethanol production. Lignocellulosic biomass can be converted to bioethanol by hydrolysis, followed by a fermentation process (Balat & Balat 2009).

During this operation, the feedstock is pre-treated through a cleaning process. It is then crushed into smaller particle sizes. Following these steps, the biomass undergoes chemical, physical or biological treatment in order to remove surrounding hemicellulose and lignin (Hamelinck et al. 2005). Hydrolysis is then performed when steam is added to the remaining free hemi-cellulose polymers (Hamelinck et al. 2005). The extracted sugars are then fermented. This process allows woody-biomass feedstocks to be converted in liquid biofuels.

This type of biofuel (biomass liquid) production is commonly known as a second generation biofuel (Zabaniotou et al. 2008). It can become a direct replacement for first generation biofuel processes, such as fermentation for bioethanol and esterification for biodiesel production. The primary benefit of second generation biofuels is that higher yields per hectare of biomass are

achieved. First generation biofuels have limited performance in terms of conversion efficiency and also require a larger amount of land-use (Suurs & Hekkert 2009).

Another type of second-generation biofuel production is through the gasification of lignocellulosic biomass and the subsequent Fisher-Tropsch process. This process converts the gaseous energy source from an air rich gasification process into liquid hydrocarbons (Suurs & Hekkert 2009). This in turn can produce biodiesel and bioethanol. A schematic of hydrolysis for bioethanol production is shown in Figure 2-7.

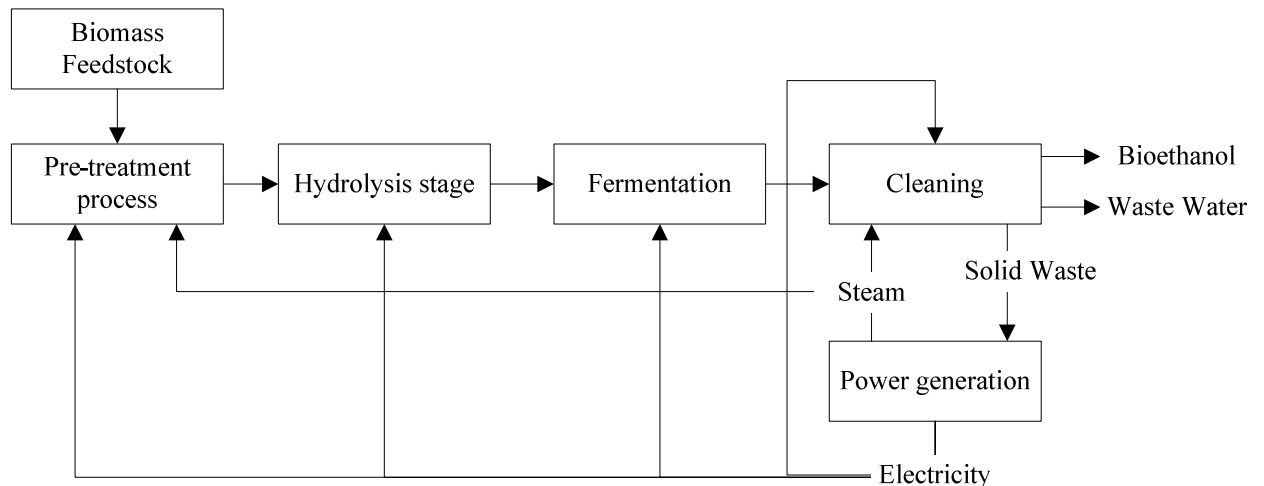


Figure 2-7 Process flow of hydrolysis fermentation. Source: (Hamelinck et al. 2005)

Anaerobic digestion (AD) – This process converts organic material directly into methane, known as biogas. Biogas is produced from the decomposition of organic material in the absence of air and sun light. The biogas is a mixture of methane (50-75%), carbon dioxide, hydrogen sulphide, ammonia and other trace elements (Ecofys 2005). Biogas can be used in a variety of combustion processes and is a direct replacement for natural gas. Biogas is considered combustible if the methane content is above 45% (J.Prior, Summerleaze Ltd. 22/05/2007, personal communication). The gas can also be cleaned (hydrogen sulphide and carbon dioxide removed) and compressed, ready to be used as a transport fuel. Feedstocks tend to be animal and human produced wastes, including municipal waste; however any biomass feedstock is suitable. The process requires biomass to have a high moisture content and relatively low total solids concentration (TS) for optimum operability.

The process undergoes four stages of biodegradation; these stages convert the carbohydrates, fats and proteins into sugars, fatty acids and amino acids (Deublein & Steinhauser 2008). Acidogenic bacteria break down the components further into hydrogen sulphide, carbon dioxide and ammonia. The molecules are broken down through a third stage to create acetic acids, carbon dioxide and hydrogen. In the final stages these are converted further into water, carbon dioxide and methane (in inverse quantity). Once the methane is extracted the waste product can also be used as a natural form of fertiliser. Fertiliser processed through AD is deemed to have beneficial properties and increased uniformity of nutrients compared to fresh manures (DEFRA 2007c).

2.2.3 Physio-chemical conversion processes

Esterification – This is the process of recovering oil from biomass crops. The oil is converted to biodiesel using an esterification process, where an alcohol is reacted with the oil. Biodiesel can in most cases be used as a direct substitute to petro-diesel. However due to its increased acidic levels it can have higher corrosion rates. Feedstocks for this conversion process include oil-based biomass such as oilseed rape, peanuts and sunflower seeds.

Other feedstocks such as coffee waste can be used to produce biodiesel. A benefit of this source is that while classified as waste it does not require any land use for production. However, the oil content of this feedstock is 10-15% and therefore the yield per input energy during the process may not be as high as conventional feedstocks (Kondamudi et al. 2008). Other waste sources such as cooking oil can also be used, ensuring that purification and filtration processes are also undertaken. A schematic has been shown in Figure 2-8 highlighting the key stages of biodiesel production. The catalyst used is usually sodium hydroxide or potassium hydroxide. This is then mixed with methanol to create methoxide. At the end of the process, the methanol can be recovered through simple distillation.

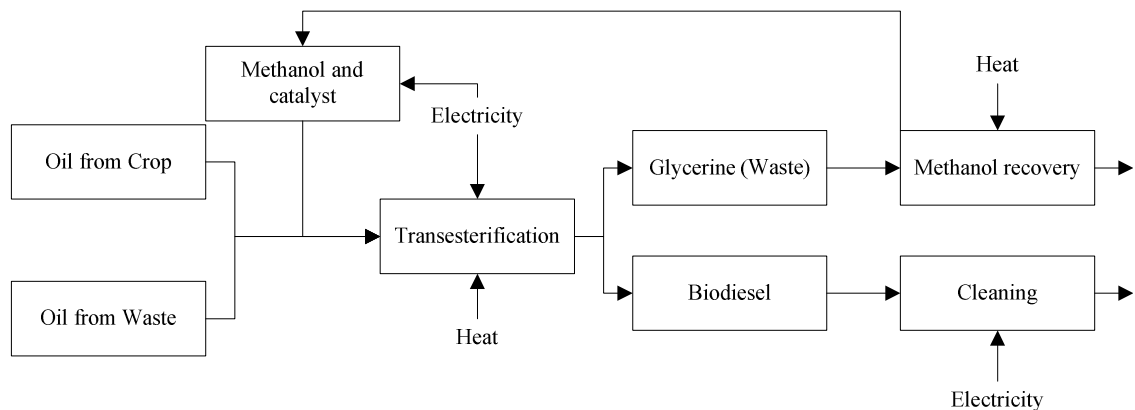


Figure 2-8 Biodiesel esterification process flow

2.2.4 Factors affecting biomass conversion to energy

When selecting the appropriate biomass conversion process (or vice versa, choosing a suitable biomass feedstock for a particular biomass conversion technology) there are a number of factors which must be considered. These are the yield or availability of the biomass, the moisture content, the calorific value within the biomass feedstock and other biomass specific properties. Additionally the energy inputs required to produce the bioenergy can also impact on the yield availability. This has been considered in detail for biogas production in Chapter 7.

The energy output of biomass feedstock is dependent on the density of the material; which is affected by the moisture content (MC). Wood density can vary from 150kg/m³ to 800kg/m³ based on the MC alone (Ecofys 2005). The MC of a feedstock is linearly related to its net calorific value (NCV). For example, if a wood had an MC of 50%, then its NCV would be half of that of a dry feedstock. The MC is a highly significant factor affecting the energy output of biomass feedstock. It is therefore important to reduce the MC to as low as possible for direct combustion (*ibid*).

Other technologies such as wet anaerobic digestion (AD) require a high MC. Usually a minimum of 80-90% MC is required in AD plants in order for optimal fermentation and ease of the material pumping through the plant. This differs significantly from direct combustion biomass, where the preferred MC would be 0%. In these two processes however, the water content has different effects on the biomass feedstock. In either case the MC has a significant impact on storage and transportation of bioenergy. This has been addressed in section 7.2.4 where the energy consumption in transport biomass fuels is examined.

For woody biomass, the term oven dry tonne (ODT) is commonly used signifying that there is no moisture concentration in the wood, hence MC = 0%. This is unrealistic and usually unachievable as there is always a moisture concentration in ambient air. This term is used as a base value for defining wood energy quantities, enabling different feedstocks to be easily compared. Energy crops such as short rotation coppice and miscanthus also have varying calorific contents which are dependant on MC. Miscanthus with a MC of 25% is reported to have between 4.7MWh/tonne and 3.6 MWh/tonne (17-13 GT/tonne) of energy content (UK Forestry Commission 2007).

Therefore, the conversion technology is chosen based on the properties of the biomass feedstock and vice versa (a suitable conversion process is selected based on the feedstock type). This highlights the critical link between these two stages of the bioenergy supply chain and that it can operate top-down (conversion technology dictating feedstock) and bottom-up (feedstock dictating conversion technology).

2.3 *Energy content of bioenergy*

The end-use of the bioenergy fuel is dependant on the internal energy and the thermal quality of the fuel. An example used by Slessor & Lewis (1979) is the comparison of wood, coal and oil. If the same calorific energy contents were released from these three sources, different quantities of mass would be involved. This is because of the fuel's energy density, i.e. the calorific energy content per unit mass. When these three fuels are combusted, although they would release the same amount of energy (say 100MJ each) they would deliver the energy at different temperatures. The heat from combusting oil is said to be more effective than coal or wood, due to the higher temperature obtained (Slessor & Lewis 1979).

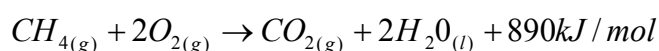
In general, solid biomass feedstocks such as woody biomass, pellets and woodchip tend to be used mainly for heat production. This is due to their lower quality of energy thus delivering energy at a lower temperature. Liquid fuels such as bioethanol and biodiesel and gaseous fuels such as methane, hydrogen and carbon monoxide (from gasification) are rarely used for heat production only (Ecofys 2005). They have a higher thermodynamic quality than solid fuels and therefore their capability of producing work will be greater. For this reason the use of these higher-grade bioenergy sources are aimed at electricity production and transport energy uses. The calorific value of bioenergy feedstocks can also differ significantly. For example methane from anaerobic digestion has an energy content of around 50 MJ/kg (net calorific value), whilst biodiesel has a net calorific value of 35.7 MJ/kg. A list of energy values of utilisable bioenergy sources has been shown in Table 2-1. These show the typical net calorific values (NCV) and gross calorific value (GCV). The table highlights the difference in energy content between solid bioenergy sources, liquid and gas bioenergy.

<i>Liquid/Gas bioenergy derivatives</i>	NCV	GCV	Unit	
Biodiesel	37.3	39-40	MJ/kg	(Gopinath et al. 2009; Stephenson et al. 2008)
Bioethanol	26.7	29.8	MJ/kg	(BERR 2003; Dong et al. 2008)
Biogas (60% CH₄)	30	33	MJ/kg	(Fitzpatrick 1998)
Methane	50	55	MJ/kg	(Fitzpatrick 1998)
Hydrogen	121	143	MJ/kg	(Varkaraki et al. 2007)
Carbon monoxide	10.1	10.1	MJ/kg	(Knoef 2005; Forestry Commission 2007)
<i>Delivered solid bioenergy sources</i>				
Wood chips (30% MC)	12.6	-	MJ/kg	(Areikin & Turley 2008)
Wood pellets (8% MC)	17.5	-	MJ/kg	(Areikin & Turley 2008)
Miscanthus bale (25% MC)	13	-	MJ/kg	(Forestry Commission 2007)
<i>Other</i>				
House coal	29	30.5	MJ/kg	(BERR 2008a)
Straw	12.8	15	MJ/kg	(BERR 2008a)
Short rotation coppice	9.3	11.1	MJ/kg	(BERR 2008a)
Landfill gas	19-23	21-25	MJ/m ³	(BERR 2008a)
Sewage gas	19-23	21-25	MJ/m ³	(BERR 2008a)

Table 2-1 Net calorific values and gross calorific values of bioenergy types

When examining the energy potential of a source or a process, the primary step is to consider the combustible energy within the source. It is called the calorific value or known as the heating value. This is the total energy emitted from a source in the form of heat when total combustion of the source has occurred. The heating value is dependant on the elemental composition, the ash content and the fuel moisture content (Knoef 2005). Another definition of calorific value is a measure of the amount of heat evolved when unit mass of a fuel is burned completely under standard conditions (Slesser 1988).

When accounting for the calorific value of a fuel, there are two terms which are commonly used. These are Net Calorific Value (NCV) and Gross Calorific value (GCV); also known as lower heating value (LHV) and higher heating value (HHV). The GCV is obtained when all the water formed by combustion is a liquid. This is a measure of the heat evolved when the products of combustion are cooled to ambient conditions (25°C) and water vapour has condensed, determining its latent heat (Slesser 1988). The NCV takes into account the heat of vaporisation of the water formed from the hydrogen in the material and the moisture (Bejan et al. 1996). This value is calculated by deducting the latent heat of condensing water from the gross value (*ibid*). The GCV can be calculated by a composition's specific heat of combustion. For example, the specific heat of combustion for methane (from basic chemical equation balancing) is as follows:



2-2

A mole of CH_4 has a weight of 16 grams; therefore, the specific heat of combustion for methane is 55.6 MJ/kg. The NCV can be calculated by subtracting the specific heat of vaporization of the water within the combustion from the GCV (therefore around 50 MJ/kg).

For woody biomass compositions, the gross calorific value (GCV) of biomass is composed of the summation of contents of carbon, hydrogen, sulphur, nitrogen and ash, all on a dry basis (Rosillo-Calle 2006). The equation for this can vary depending on the biomass resource used (Kathiravale et al. 2003). The typical difference between the NCV and the GCV for woody biomass feedstocks is around 1.3MJ/kg according to Rosillo-Calle (2006). Energy calculations of processes often use NCV in European analyses, whilst USA analyses tend to use GCV. Throughout this study the NCV is used during calculations, unless stated otherwise.

2.4 *Comparison of bioenergy pathways*

Studies have been undertaken to determine the optimal biomass for different energy uses. Literature is often contradictory on whether biomass is more cost effective for transport biofuels, heat or electricity (Grahm et al. 2007). Most studies carried out to date have assessed the potential of bioenergy based on economic factors (BERR 2007c; Hansson & Berndes 2009). Studies which concentrate on other aspects of bioenergy use, for example GHG emissions, narrow the scope of studies to particular end-use fuels such as biofuels for transport only (Cherubini et al. 2009), and fail to assess the bioenergy pathway using alternative appraisal techniques. Other techniques can include economic and social implications, along with other environmental impacts.

It is apparent that the suitability of a bioenergy pathway is dependant on the location of the resource. Due to biomass feedstock having a relatively lower energy density compared to fossil resources, the transport of biomass has a large impact on the energy output of the feedstock. Additionally, the growth of different biomass crops is affected by geographic location due to climatic conditions. This is also true for waste feedstocks. For example, an AD plant should ideally be situated near a farm or group of farms in order for the plant to be as efficient as possible. Therefore bioenergy pathways are intrinsically unique and dependant on location, geographical and climatic circumstances and the end-use energy requirement. To compare bioenergy production and use emissions and its overall impact towards the environment is difficult and not straightforward. The environmental life cycle assessment of biogas production, documented in Chapter 8, highlights the level of detail at which analyses must be taken.

When determining the optimum bioenergy type for a prospective development, there are two techniques which can be used. The first is to determine the optimum bioenergy pathway based on feedstock availability and climatic/geographical conditions, termed as a bottom-up approach. This is where the feedstock quality and availability is considered, as well as the bioenergy conversion process selection and energy output of the plant. The second method, a top-down approach would determine the energy requirements and then implement a bioenergy conversion technology able to deliver the energy. This would be followed by establishing the feedstock availability.

Within a single pathway, such as biogas production, the efficiency can vary greatly depending on feedstock, size, technology use and energy end-use. Therefore, bioenergy pathways cannot be easily compared, due to their large variability. Conversion techniques and uses for bioenergy are numerous with some more established than others. For developers it can be difficult to determine which bioenergy pathway is most effective. As a result, developers can find the vastness of bioenergy pathways a barrier to the development and uptake of bioenergy conversion processes (Adams et al. 2008). This also has a similar impact on public perception and social acceptance of bioenergy, which has been examined further in Chapter 4 (Adams et al. 2008). Despite this, several attempts have been made to publish the comparison of biomass conversion processes and bioenergy uses amongst a number of different criteria. A study issued by FAO (2004) and conducted by Kaltschmitt et al. (2001) showed a comparison of different conversion routes.

	Charcoal Production and Use for Heat	Syngas production for electricity	Pyrolysis oil for transport fuel	Vegetable Oil for transport	Vegetable oil esterification for transport	Alcohol production for transport	Biogas production for electricity generation
<i>Feedstock</i>							
By-products	++	+++	+++				++
Energy Crops	+++	+++	+++	+++	+++	+++	+
<i>Conversion Techniques</i>							
Technology	+++	++	+	+++	+++	+++	++
System Technology	+++	+	+	+++	++	++	++
<i>System Aspects</i>							
System Integration	+	+++	+++	+	+++	+++	++
Environmental Benefits	++	+++	+++	+++	+++	+++	++
Costs	++	+	+	+	+	+	+
Cost Reduction Potential	+	+++	+++	+	+	+	++

Table 2-2 Comparison of biomass conversion pathways (FAO 2004; Kaltschmitt et al. 2001)

+++ very promising; ++ promising, + less promising.

Table 2-2 compares a number of typical bioenergy conversion routes, which represent the potential success of implementation of these bioenergy pathways. For example syngas production from gasification can use a wide variety of feedstock (therefore very promising), whilst the feasibility of system technology and operability is less certain and therefore less financially feasible. This is also true for pyrolysis as this conversion process still remains in its infancy in the UK (Mullis 2007).

The table shows that bioenergy pathways rated 'less promising' with regards to cost implications mirror relatively well the actual establishment of that particular technology today. Large-scale bioethanol and biodiesel plants which promised to supply vast amounts of first generation biofuels have halted due to financial obstacles (GSF 2008). Therefore the study from FAO (2004) represents this outcome extremely accurately.

Further examination of Table 2-2 highlights the complexity and the disputability of the results. If one were to take environmental benefits as an example of decision criteria, first generation biofuels offered very promising environmental benefits. Meanwhile, AD for electricity offered relatively less benefits. Established studies (The Royal Society 2008) have clearly highlighted the environmental issues of using first generation biofuels, whilst other studies highlight the environmental benefits of producing biogas (Zah et al. 2007).

When discussing the potential role of bioenergy, it is worth considering the benefits and detriments of the energy source. An advantage of all bioenergy is that it can reduce the dependency on fossil fuel resources and subsequently reduce carbon dioxide emissions (Demirbas et al. 2009). Other benefits are valid only to particular bioenergy pathways. These include for example, the use of valuable fertiliser from the by-product of biogas production. Additionally, biodiesel production from waste oils can improve waste minimisation and recover valuable energy.

The detrimental effects of bioenergy may prevent the development of this energy source. The most common issue is the perception of the intensive land-use requirements for bioenergy production. Some biomass feedstocks require land which could otherwise be used for food growth (Hall & Scrase 1998). This issue raises the potential risk of deforestation in countries keen to harvest biomass for transport fuel due to the financial rewards (RCEP 2004). The impact of energy intensive biomass feedstock can also contribute detrimentally to the use of bioenergy. This particular point will be discussed further in Chapter 7, through the use of energy analysis.

2.5 Summary and following steps for research

This chapter gives an introduction to the use of biomass for energy purposes. An appreciation of how biomass can be converted into energy forms has been established, highlighting the most common bioenergy conversion processes. The chapter also emphasizes the difficulty in comparing or amalgamating bioenergy pathways when a cross-comparison is required.

It has been established that biomass to bioenergy conversion processes are numerous and diverse. These bioenergy pathways are dictated primarily by the feedstock availability and the end-use of the bioenergy. Due to biomass' relatively low energy density compared to fossil fuels, transportation of this energy is critical in determining the type of bioenergy conversion process adopted and the scale at which it should be operated. Literature shows that comparison of bioenergy pathways have been made (FAO 2004; Kaltschmitt et al. 2001; Zah et al. 2007), however due to the number of factors which could affect each pathway, it has been concluded that these are limited and not representative through the range of each conversion process.

The findings conclude that the multiple pathways of bioenergy can perform very differently in terms of energy output, environmental benefits or detriments and economically. To assess the suitability of a bioenergy pathway an integration of appraisal techniques must be undertaken. These techniques should encompass all areas of sustainable development (Parkin 2000). In order to assess the potential of bioenergy pathways an integrated appraisal of the environmental, thermodynamic and economic considerations should be undertaken. This

technique has been developed specifically for the case of the South West of England and is used and reported in Chapters 6, 7, 8 and 9.

In light of the above, the technique used for this thesis is called a multi appraisal methodology. The thesis sets a plausible integrated methodology, which enables the holistic assessment of a bioenergy pathway. The appraisal technique also coheres with other studies from Kaltschmitt et al. (2001), where bioenergy pathways have been assessed based on conversion processes (net-energy), environmental benefits (lifecycle assessment) and cost reduction appraisal (financial considerations).

The purpose of the thesis is to determine the potential of bioenergy in the South West of England. In agreement with the UKERC, it is acknowledged that to create a significant and detailed assessment of the bioenergy potential in the region, the multi appraisal technique should be carried out on a single bioenergy pathway. The bioenergy pathway chosen for this study was determined from the biomass resource assessment carried out for the region and reported in Chapter 3. Based on these results, the most suitable bioenergy pathway was chosen and analysed further.

3 BIOENERGY RESOURCE ASSESSMENT FOR THE SOUTH WEST OF ENGLAND

A bioenergy pathway must be selected in order to carry out a multi appraisal technique, as shown in Figure 2-3. The pathway should be chosen based on the most abundant or available biomass resource. This chapter addresses this requirement; additionally it offers a perspective of the total biomass resource *currently generated* in the South West of England and compares these findings against the *current potential resource* and the *future potential resource*. An overview of the general resource flows and energy uses in the region are also depicted in the chapter to contextualise the resource assessment findings. The work has been published in the Journal of Energy, Institute of Civil Engineering (Hammond et al. 2008a), where the present author was lead author. This has been reproduced in Appendix D.

3.1 Climate and land use

The South West of England is considered to have good climatic conditions for the growth of biomass for bioenergy. Overall the UK has a wetter climate in the west, compared to the east, and experiences warmer temperatures in the South compared to the north, shown in Figure 3-1 (McKendry 2002a). The South West's climatic conditions make it favourable for agriculture and soil formation. However, the high rainfall experienced in the region leads to impermeability of soils which causes water logging (Findlay 1984).

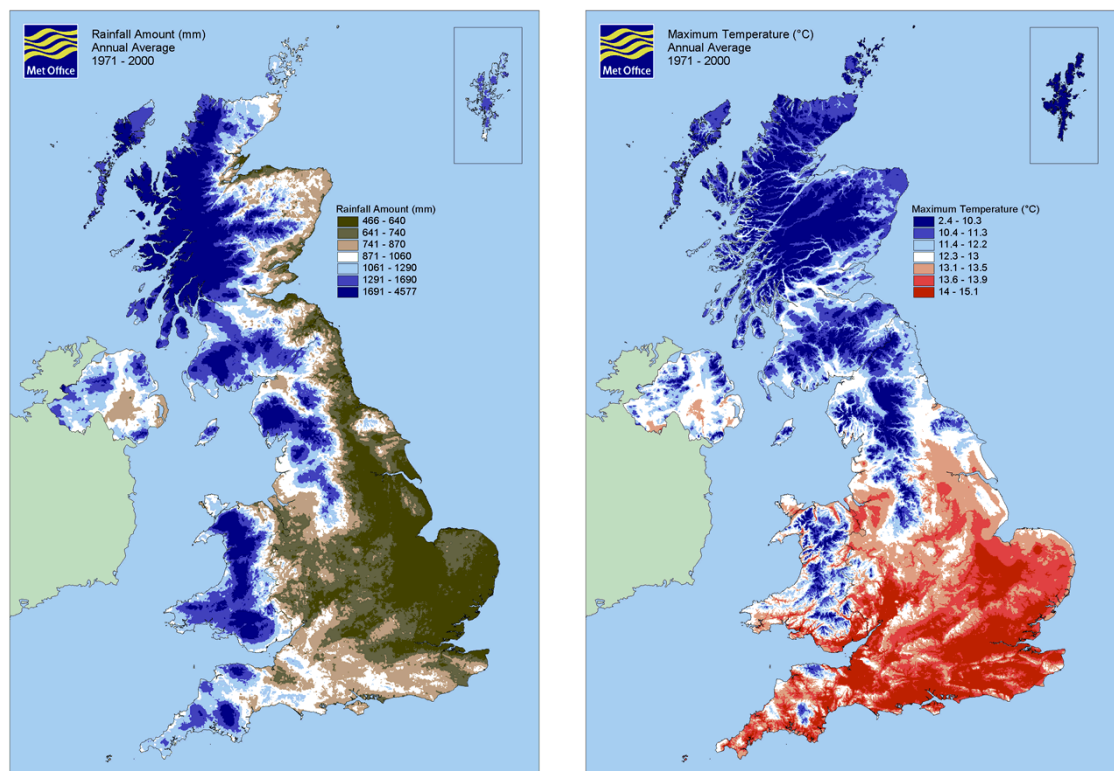


Figure 3-1 Left: Annual average rainfall - Right: Average annual temperature. Source: (Met Office 2007)

The South West of England is the largest region in England with a total land covering of 2,382,900 hectares. With a population of just under 5 million, its population density is one of the lowest in England. Land use in the region is heavily dominated by agriculture. This type of land use accounts for 80% of total land in the region (DEFRA 2007b). Agricultural land

cover has remained relatively consistent over the last 30 years and is seen as a secure source of income for many landowners in the region (Figure 3-2).

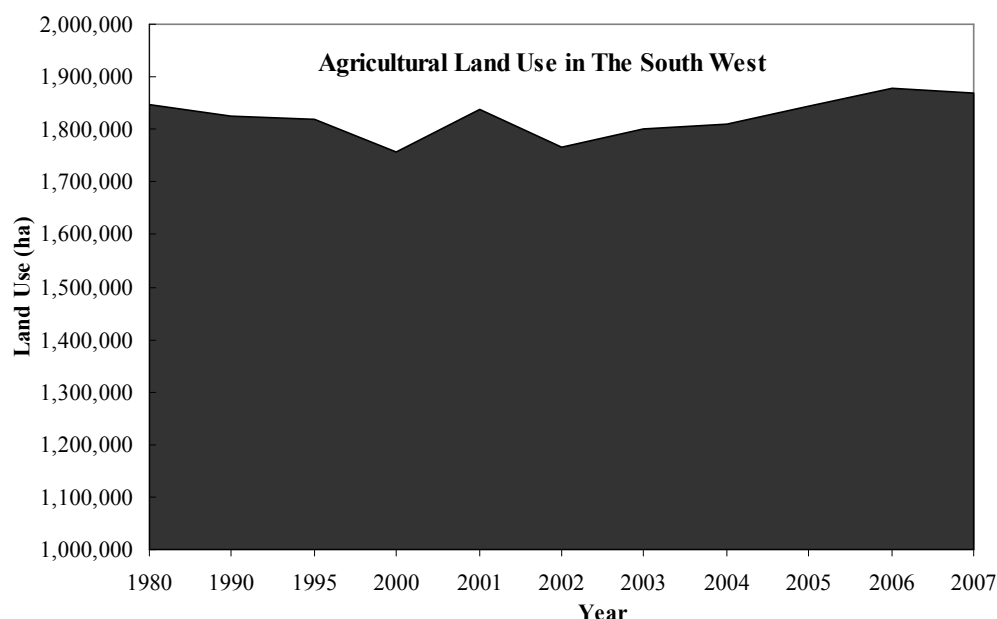


Figure 3-2 Land area allocated for agriculture in the South West of England (DEFRA 2008b)

Although agriculture dominates the regional land use, in terms of the economics of goods and services produced (Gross Value Added) this sector contributes to only 1.8% of the region's total GVA. The region's agricultural land is divided between arable land and permanent grassland. Arable land is used for crops such as wheat, barley, oats, potatoes, sugar beet, oilseed rape, maize etc. Permanent grassland, of which there is just under 1 million hectares, is more suited to dairy farming (this accounts for 65% of the total agricultural land).

Animal Species	South West Total	England Total	Percentage of England	Regional Rank
Total Cattle	1,717,871	5,378,028	31.9%	1st
Dairy herd only	464,180	1,290,230	36.0%	1st
Total Piggery	487,877	4,057,433	12.0%	4th
Total Sheep	3,256,412	15,673,409	20.8%	1st
Total Goats	27,337	82,774	33.0%	1st
Total Chicken	11,704,348	84,712,916	13.8%	4th
Total Fowl	19,264,593	120,942,144	15.9%	3rd
Total Ducks	83,756	3,249,372	2.6%	5th
Total Geese	28,138	171,943	16.4%	2nd

Table 3-1 Livestock for agriculture in the South West of England (DEFRA 2008b)

The region's extensive permanent grassland, accounting for nearly 30% of the country's total permanent grassland, signifies that arable crop farming is relatively limited, based on arable crop area per total agricultural land area. In 2007 however, the region was the leading producer of maize (DEFRA 2007b). Up until the early 1940's intensive cereal production such

as wheat, barley and oats was fairly uncommon and even in 1980 this was considered to be a relatively new field for farmers in the South West (Findlay 1984).

Livestock numbers within the region are amongst the highest in England (Table 3-1). Although some livestock types have experienced a decline in recent years (dairy cattle, pig and sheep), other farming activities have increased such as the beef herd. Between 1987 and 2000 this sector experienced a 57% increase in holdings (MAFF 2000). Currently beef herd livestock population accounts for 31% of total cattle in the South West.

3.1.1 Forestry and woodland

Woodland cover in the South West of England represents 8.9% of the total land area in the region, constituting 212,022 ha (Forestry Commission 2002). This is broadly similar to the woodland cover for England at around 8.4%. Woodland in the region is dominated by broadleaved woodland, accountable for 56.7% of total woodland and conifer woodland representing 22.8%. Other plantations include mixed species (14%), and coppiced woodland (Forestry Commission 2002). Of all the woodland in the region, only 17% is Forestry Commission owned, whilst the remaining 83% is divided between personal woodland, business, charity, local authority and other public ownership. This is just below the country's average of 22% ownership by the Forestry Commission.

Woodland cover in the region has steadily increased and has nearly doubled over the past 100 years, as can be seen in Figure 3-3. This steady growth signifies the drive to improve woodland cover in the region either for sustainability and conservation motives (aided by financial drivers) or a drive to improve landscape architecture. New woodland plantations have been between 100 ha to 300 ha per year from 1997 and 2002 (Wall et al. 2002). It is estimated that up to 50% more timber could be harvested sustainably at present (Wall et al. 2002).

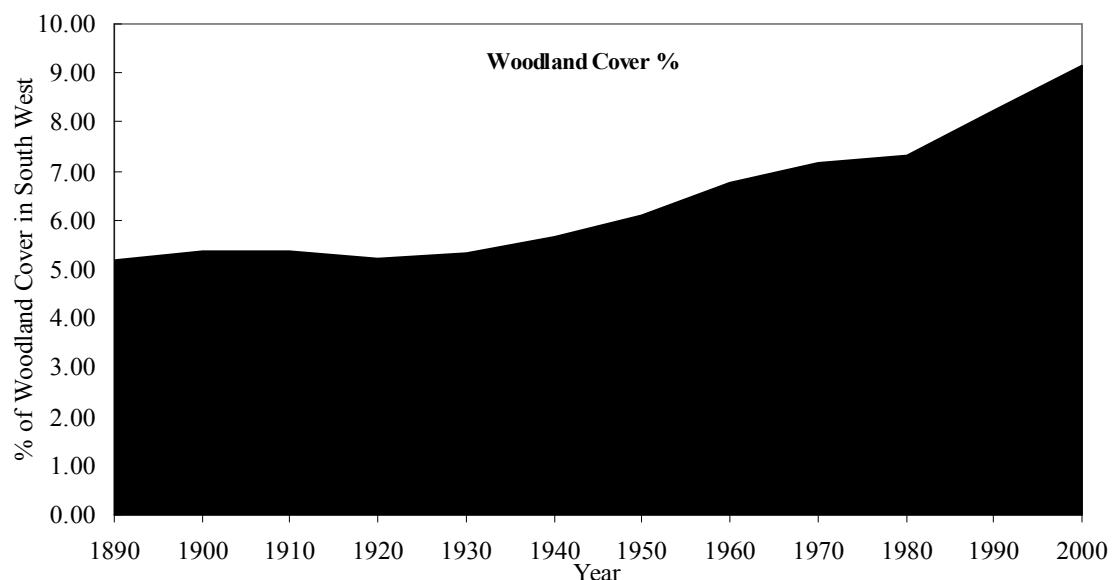


Figure 3-3 Woodland cover in the South West of England (1890-2000) (Forestry Commission 2002)

A report commissioned by the Department of Trade and Industry (now the Department for Business, Enterprise and Regulatory Reform) estimated that the present annual production of available biomass through thinning or felling totalled around 460,000 oven dry tonnes (ODT) per year (McKay 2003). This was the highest yield for any region in England and contributed to over 20% of the country's potential. Though this estimate signifies the high potential for woodfuel in the South West, a large percentage has pre-allocated markets such as construction and the furniture industry.

3.1.2 Waste flows

Waste is considered an important resource for energy production. As described previously, there are a number of techniques for its energy extraction. Although waste is widely considered a burden on society which needs to be reduced (DEFRA 2007d), it does provide a stable and secure source of energy production independent of climatic or seasonal conditions.

Waste not derived from agriculture can be classified into three main groups: municipal solid waste (MSW), commercial & industrial (C&I) and construction & demolition (C&D). MSW incorporates all household wastes and wastes from civic amenity sites. This type of waste generally contains a higher percentage of organic content. C&I waste includes paper, food, electrical equipment, chemicals and other wastes. This can also be a good source of energy if it has a high organic matter percentage. C&D waste includes construction materials such as concrete, timber, plastics and metals. Concrete is accountable for nearly a quarter of all C&D waste in the region (South West Regional Assembly 2004).

During 2007-2008, just under 3 million tonnes of MSW were collected in the South West of England. This figure has remained between 2.5-3 million for the past 7 years (DEFRA 2008c). Of this total just under 60% is sent to landfill, a figure which has experienced a gradual decline from 82% since 2001 (DEFRA 2008c). This decline in landfill use can be seen across England. This is due to mechanisms put in place to reduce the amount of waste entering landfill sites, through the Waste and Emissions Trading Act (2003) and the Landfill Allowance Trading Scheme (LATS). As landfill waste has declined, the use of recycling and composting has increased to over 40% for 2007/2008 and has been increasing since 2001. At present, the South West of England has the highest recycling rates in England (DEFRA 2008c).

In 2004 a regional waste strategy was introduced for the South West with the aim to considerably reduce the waste generated in the region. The strategy aimed to reduce landfill use to 20% and increase the use of recycling up to 45%. The ultimate aim was to "become a minimum waste producer by 2030" (South West Regional Assembly 2004).

3.1.3 Energy focus on the South West of England

In 2006, the South West was recorded as the third lowest consumer of energy for transport, domestic, commercial and industrial sectors, with a total energy consumption of 250 TWh as shown in Figure 3-4 (DECC 2010c). Energy consumption per capita is also relatively low at around 27MWh/person/year. In addition to this, due to the region's extensive total land covering, energy use per unit hectare shows that the South West has the lowest energy consumption density, at a mere 55MWh/ha; nearly 20 times lower than London. This can be good representation of the potential for bioenergy in the South West as the region offers a large biomass working area in comparison to the energy consumption.

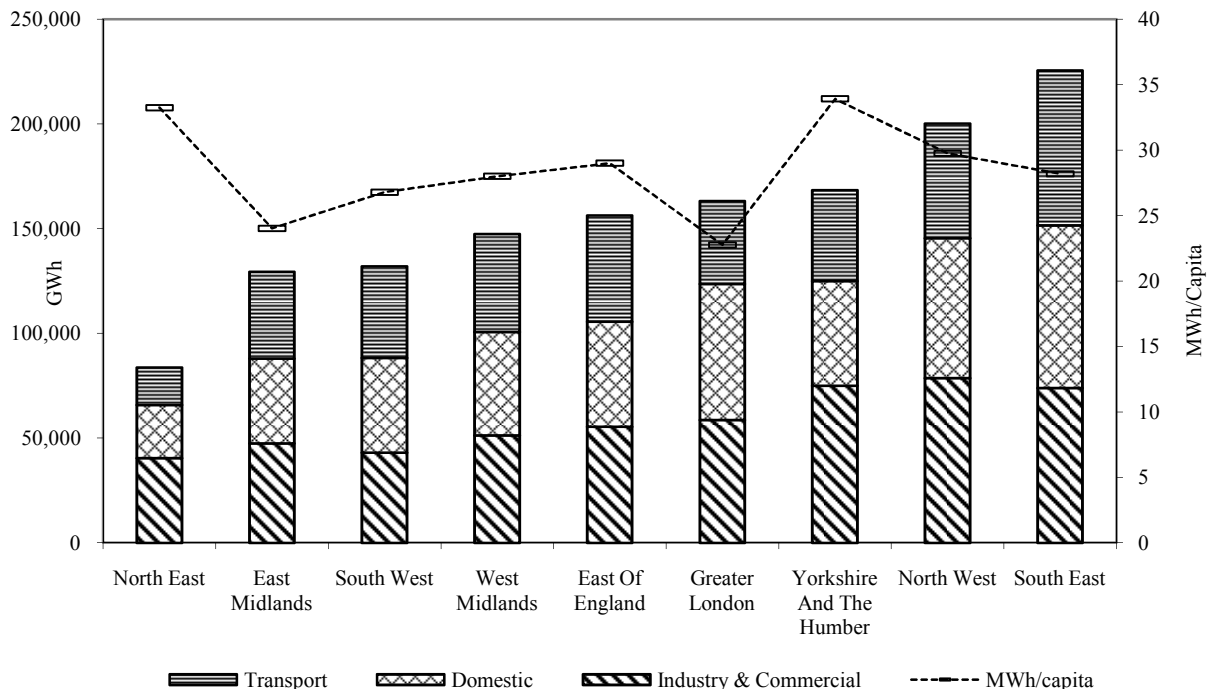


Figure 3-4 2006 Primary energy consumption for England regions; data obtained from DECC (2010c)

With only 151MW of renewable heat and electricity generation in 2008 (RegenSW 2008), the remaining 99.1% of energy use in the South West is produced either from fossil based fuels such as coal, oil and gas or nuclear. As such, the overpowering reliance on fossil-based fuels can clearly be seen even at a regional level for the South West.

Energy consumption can be closely linked to the emission of carbon dioxide (shown in Figure 3-5). When compared to other regions in England the results are predictably parallel to the overall energy use per region (DEFRA 2006). This highlights the strong link between energy consumption and carbon emissions. With national targets to reduce carbon emissions (BERR 2007a) the dependency on fossil fuels must be reduced.

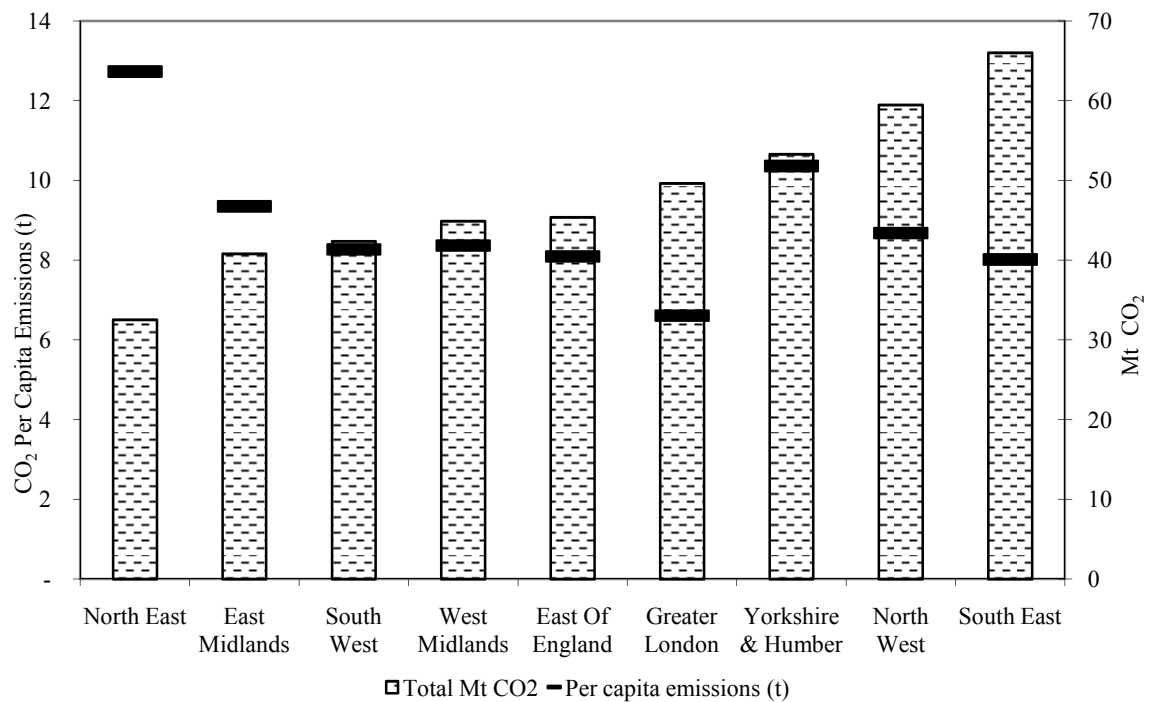


Figure 3-5 Carbon dioxide emissions in England for 2006; data from DEFRA (2006)

3.2 Bioenergy resource assessment – methodology approach

In order to determine the biomass potential for the South West of England, a quantified resource assessment of the biomass was carried out. A resource assessment quantifies the supply of available biomass for a specific land area. In general, resource assessments carried out, specifically for the South West of England, have concentrated on specifying the biomass conversion technologies available, the economic aspects of the biomass in relation to the conversion technology and subsequently the feasibility of utilisable biomass (Capener et al. 2005; O'Rourke 2001). Other studies consider only certain biomass resources and therefore do not account for the whole of the bioenergy potential (Scholes 1998). Studies which primarily consider economic viability and conversion technology feasibility are called a 'top-down' approach.

The methodology carried out in this study examined bioenergy adopting a bottom-up approach. A bottom-up resource assessment signifies that the primary considerations of the assessment include physical material availability. This is subsequently followed by allocating other constraints such as economic considerations, sustainability constraints and accessibility concerns. The ultimate end-use bioenergy was not considered in this section.

This approach was considered suitable for the study as it enabled all biomass resources to be considered and made comparable to each other. For example, if the deployment of a technology was a primary consideration for a resource assessment, this would dictate the biomass resource required. This would not take into account the natural current status of the resources available within the region. The risk associated with a bottom-up approach is the result tends to determine the potential supply of biomass, as opposed to the actual supply.

When the potential supply of biomass is studied, the feasibility of collecting and using this supply should also be considered. This ultimately determines the actual supply of bioenergy.

Biomass resources vary greatly and as suggested earlier, can be categorised into four main groups: woody plants, herbaceous plants, aquatic plants and wastes (McKendry 2002a). For simplicity, biomass can be divided into two main categories, woody biomass and non-woody biomass (Rosillo-Calle 2006), which covers the entire biomass range.

Woody-biomass comprises of organic material containing ligneous content, it has a slower growth rate in comparison to herbaceous plants and has a compilation of tightly bound fibres (McKendry 2002a). Non-woody biomass includes plants and also organic wastes. These generally have a higher moisture content. Non-woody biomass can then be divided into subsequent categories such as manures, herbaceous crops and processing wastes.

Separating biomass resources into two categories avoids any possibility of overlap or ‘double accounting’ for biomass resources. Upon completion of the data collection for both woody and non-woody biomass, it was necessary to determine the actual supply of biomass rather than the potential supply. This provided a more precise figure of the biomass availability for the region. Constraints were put in place to distinguish whether a supply could ultimately be used as a biomass resource. These constraints included the elimination of resource with pre-allocated markets such as wood resource used by the building industry. These constraints became apparent when assessing literature sources and databases and have been documented within the resource assessment results.

3.2.1 Woody biomass resource within the South West

For this part of the resource assessment the following biomass resources were considered:

- Forest and woodland biomass and residue;
- Energy plantations (lignin type – Short rotation coppice (SRC)). Although miscanthus is defined as an herbaceous plant, it was considered to be a woody biomass as it is low in moisture content and can be used for biomass combustion. The lignin content of miscanthus is approximately 17%, whilst for willow, which is a type of SRC the lignin content is around 19%;
- Arboriculture plantations and residue.

The data collection procedure for the woody biomass resource assessment is displayed in Figure 3-6. The flowchart represents the routes considered for the research. The procedure for the resource assessment was divided into three areas: energy plantations, agro-industrial and processed biomass. Energy plantations included dedicated energy plantations such as short rotation coppice (SRC) and miscanthus. It also included forest and woodland biomass and residue. Agro-industrial plantations consisted of arboriculture residues, such as shrubs, hedges etc. Processed biomass included residues from regional sawmills and other processing wastes. This section also accounted for packaging and pallet wastes within the region. Primary data was collated from Forestry Commission data. However, other sources were included:

- Tree surgeon survey – An analysis of the number of tree surgeons and the annual yield was determined. This information was gathered by creating a tree surgeon database for the South West, followed by contacting a sample size (20) of the regional tree-surgeon population to determine the average annual waste wood production. The survey was carried out by telephone conversation to the randomly selected tree surgeons.
- Sawmill Survey – Yield data for this section was carried out similarly to the tree-surgeon survey. A randomly selected number of saw-mills (20) were contacted to determine the amount of wood waste produced per year.
- Current wood-fuel consumption data – This data was collected from regional agencies such as Renewable Energy Association and Regen SW (RegenSW 2008).

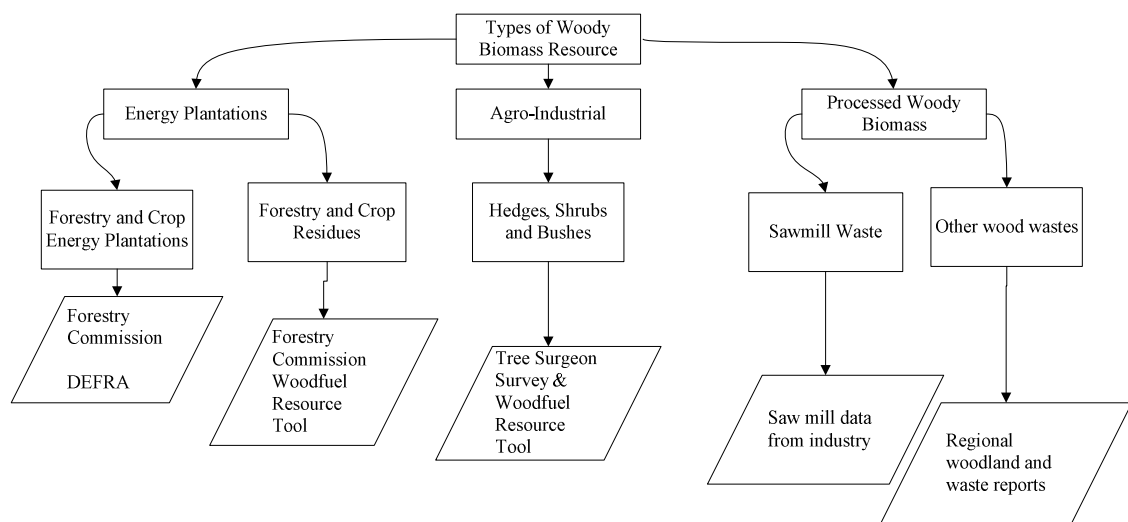


Figure 3-6 Data sources for woody biomass resource assessment

3.2.2 Non-woody biomass resource within the South West

The methodology for non-woody biomass resource assessment is similar to that of woody biomass. Non-woody biomass, as described previously includes plantations and waste. In detail, non-woody biomass comprises of:

- Agricultural crops – Crops currently grown for human and animal consumption such as wheat, barley and oilseed rape;
- Crop residues – Residues from processing agricultural crops including straw, silage, seed skins etc;
- Herbaceous crops – Crops with a dedicated growing season. Growing seasons can be annual or perennial;
- Animal Waste – Wastes produced through manures;
- Other wastes with organic content – These include household and industry wastes termed as municipal solid waste (MSW) and commercial & industrial waste (C&I).

The methodology flowchart has been shown in Figure 3-7. However due to the varying types of non-woody biomass it was considered easier to separate non-woody plantations and non-woody waste. The flowchart shows how this was undertaken.

The waste and residue resource assessment is more diverse than non-woody plantations and woody biomass. Therefore, potentially it could be the area with highest percentage error in the findings. These errors can arise due to varying calorific contents of materials, which ultimately have an impact on the bioenergy potential. This process involved looking at agricultural plantations, crop residues, animal waste production and other waste sources for the South West of England.

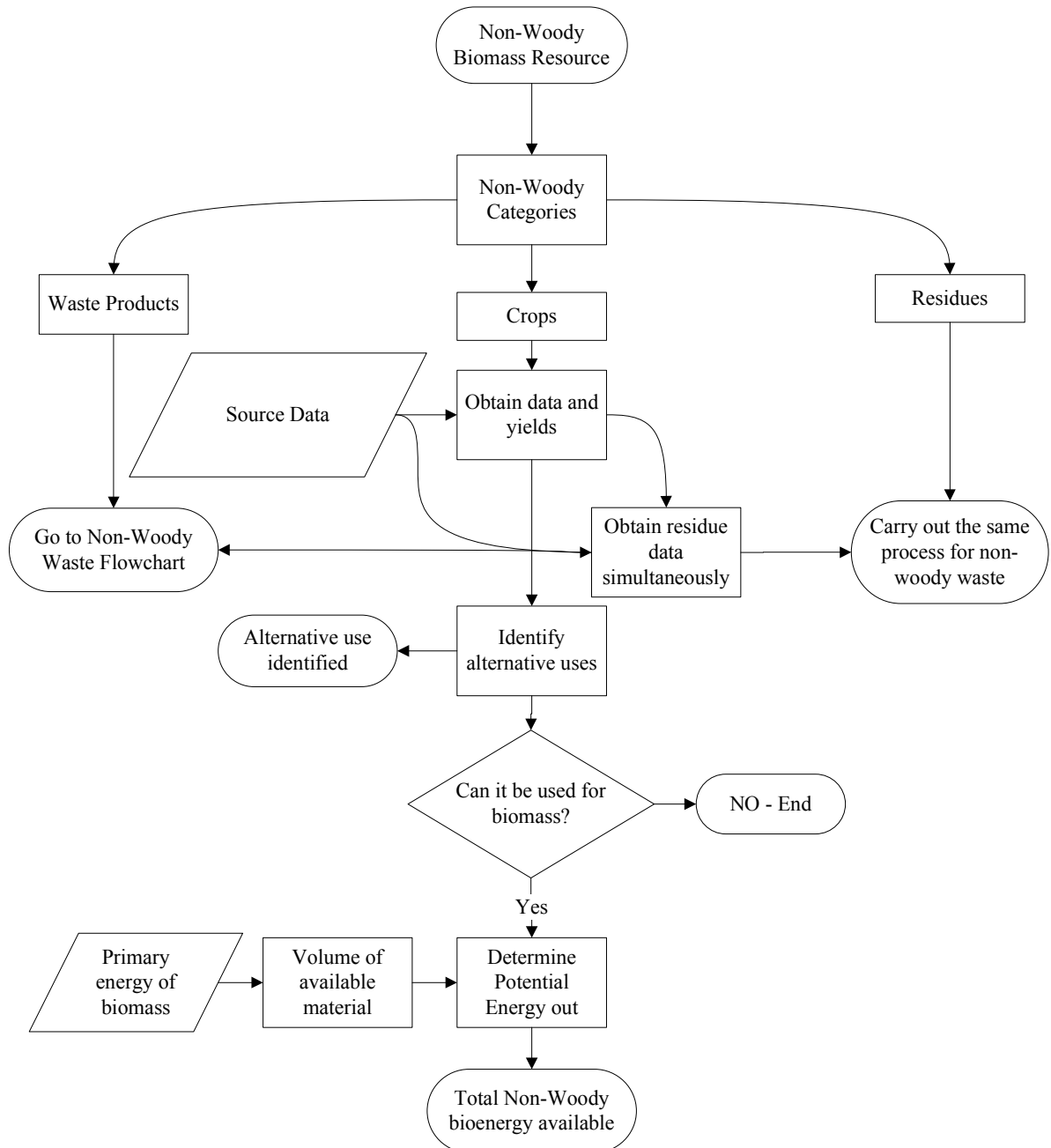


Figure 3-7 Resource assessment methodology for non-woody biomass

3.3 *Determining the fuel energy content of biomass resources*

The primary aim of the study was to determine the resource which contributed the highest towards bioenergy supply. Additionally, an overall appreciation of all the resources was also required. Biomass resources have varying energy density which is a measure of the energy as a fuel, available per unit mass or volume. Representing results in terms of mass or volume was considered misrepresentative as it would be difficult to understand whether 1 tonne of oil seed rape was more attractive than 1 tonne of miscanthus.

The use of mass or volume as a measure of resource availability for biomass was therefore considered inappropriate and a measure in terms of energy potential as a fuel resource would be more suitable. A resource assessment encompassing a wide range of biomasses, such as this, required a uniform measure of potential. As a result, the net calorific value (NCV) of the resources was used as a measure of the biomass potential.

The NCV of an energy source takes into account the total energy available and does not address the end-use energy conversion efficiency of an energy source (BERR 2008a). The conversion of biomass into usable bioenergy such as wood chip, biofuels, biogas and syngas, have associated conversion efficiencies. For example, biogas production from AD is only able to recover a percentage of the NCV of the feedstock due to its conversion efficiency. Furthermore, if that biogas were then converted into electricity, the conversion efficiency of electricity production would reduce the actual available energy.

The use of NCV is a valuable comparison tool for measuring the performance of different bioenergy feedstocks. However, when interpreting the results in terms of total bioenergy potential for the South West of England, they should only represent the total energy, not the delivered energy. In this study the results were represented in terms of NCV as this gave a clearer interpretation of the bioenergy potential. This is similar to the methodology laid out by Rosillo-Calle (2006); currently one of the most comprehensive biomass resource assessment methodologies published.

Table 3-2 displays the comparison between fossil based fuels (denoted by F) and some biomass feedstocks. Generally, primary renewable energy sources as shown in the table have a lower overall calorific content compared to fossil-based fuels. Secondary resources, such as the ones converted through a bioenergy conversion process, have a higher NCV than primary resources. The moisture concentration in feedstocks such as wood also significantly affects the NCV of the feedstock.

Fuel Type	GCV GJ/tonne	NCV GJ/tonne
Coal – F	26.9	25.6
Natural gas - F	39.7	35.7
LPG (propane & butane) – F	49.5	47
Petrol oil – F	43.6	41.5
Diesel – F	45.5	43.3
LPG	49.3	45.9
Charcoal	-	28
Hydrogen gas	-	120
Miscanthus (25% MC)	-	13
Poultry	-	13.5
Cattle (dry matter)	-	14
Methanol	-	21
Ethanol	-	28
Domestic wood	13.9	12.3
Oven Dry wood	20.2	18.9
Wood (10% MC)	20.2	16.56
Wood (30% MC)	20.2	12.34
Wood (50% MC)	20.2	8.12
Wood (70% MC)	20.2	3.89
Short rotation coppice	11.1	9.3
Straw	15	12.8
Poultry litter	8.8	7.4
Municipal solid waste	9.5	6.7
Methane	55.6	50.6
Landfill gas	21	19
Sewage gas	21	19
Biogas (60% CH ₄)	-	20

Table 3-2 Net calorific value and gross calorific value of various energy sources (BERR 2008a; Rosillo-Calle 2006; Cao & Zheng 2006; Seo et al. 2007; Slessor 1988)

3.4 Results

The resource collection methodologies for woody and non-woody biomass were carried out for three different resource assessments. These assessments were used to give an understanding of the current production of bioenergy, the maximum current potential of bioenergy and the future maximum potential. The three assessments have been detailed below:

Resource Assessment A – This was an assessment of the current bioenergy production in the South West of England.

Resource Assessment B – This assessed the current theoretical maximum bioenergy potential for the South West of England. This assessment did not take into account estimates for future crop growth, but only currently available feedstocks, wastes and other resources.

Resource Assessment C – This examined the future theoretical maximum bioenergy potential for the South West of England. It investigated the feedstocks from assessment B and determined whether this could increase or decrease up until 2020.

3.4.1 Resource assessment A

The first resource assessment examined the current bioenergy production in the South West. This incorporated all sources of bioenergy feedstocks. From the assessment, it was revealed that energy from waste (landfill gas, sewage, farm biogas and other forms of energy-from-waste) is currently the largest contributor to bioenergy in the South West. This energy accounted for 54% of the total bioenergy as shown in Figure 3-8. The largest land-fill energy recovery plant in the South West is situated in Dorset (Whites Pitt) and has a peak capacity of 6.92MW of electrical power. The majority of energy produced from waste is derived from landfill gas energy production situated across 22 sites within the region. Landfill sites have a larger energy capacity, as opposed to sewage-gas energy plants due to the size of biomass available at the site. Sewage-gas electricity generation plants do not usually exceed 1MW in size.

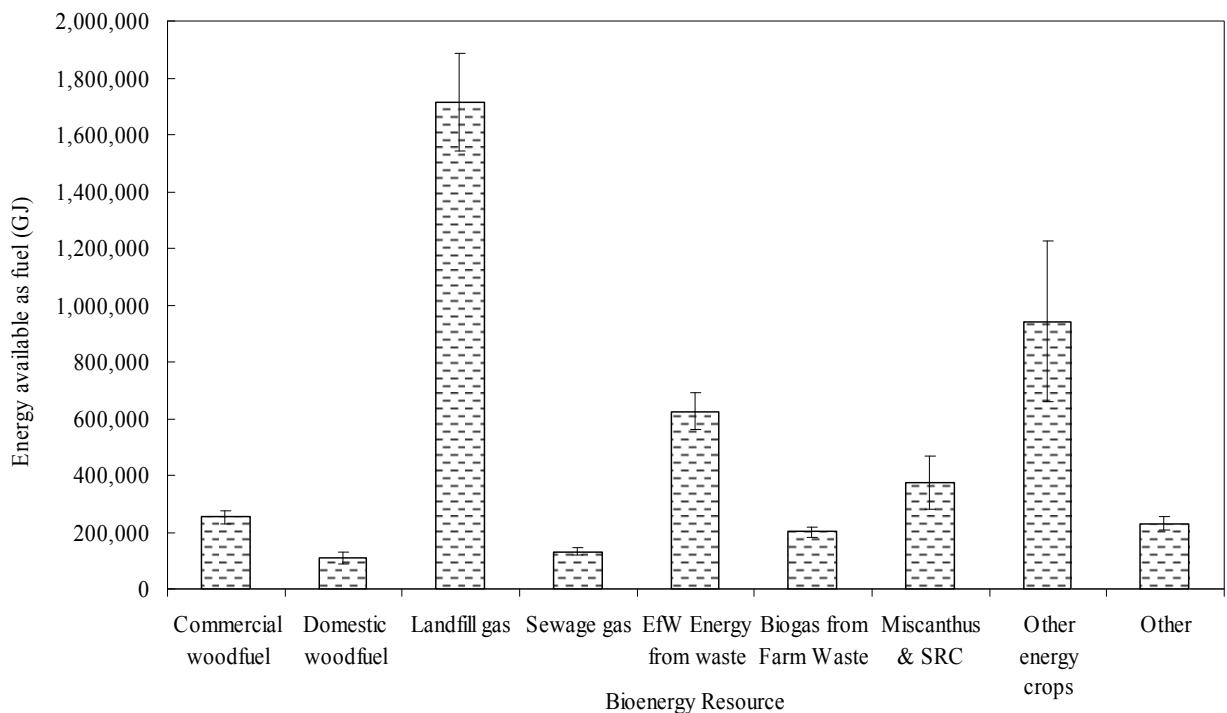


Figure 3-8 Current available energy from present biomass consumption

Biodiesel production from oil seed rape was classified as “other energy crops” within the study. The production of biodiesel is relatively new as oilseed rape (OSR) plantations have been generally used for animal and human consumption. The increased production of biofuels has been driven by Government targets to implement renewable resources in transport fuels (RFA 2008a). However this target has been pushed back to 2013/2014 after concerns of uncontrolled expansion through the use of biofuels were raised by the Gallagher Review in 2008 (RFA 2008b). Therefore bioethanol and biodiesel production is expected to increase within the region. The UK’s largest biodiesel plant is to be built in the region within the coming years and is proposed to ultimately produce up to 500,000 tonnes of biodiesel per year

(ABS 2008). However, the source of the feedstock was unclear and therefore was not considered within the study.

Biogas from anaerobic digestion (AD) accounted for 4% of the total bioenergy production in the region. There are a number of plants situated in more rural locations where animal and food waste is readily accessible (Maltin 2004; J. Prior, Summerleaze Ltd. 22/05/2007, personal communication). Woodfuel contributes to the remaining 8% of the regional bioenergy mix. This source of biomass is used mainly for heating, as it is considered too costly for electricity generation alone. The lack of managed woodland and the limited plants within suitable transport distances represents significant barriers to woodfuel growth.

3.4.2 Resource assessment B

The second stage of the analysis considered the current maximum available bioenergy potential in the South West. The maximum availability took into account the theoretically obtainable biomass. This included bioenergy that was currently un-marketed as a resource or where markets could be altered to allow for increased bioenergy generation. The study did not consider altering food or timber production markets, it analysed bioenergy on a material-flow basis, assessing the availability of material suitable for bioenergy. The assessment examined all possible feedstocks suitable for bioenergy as shown in Fig 3-9.

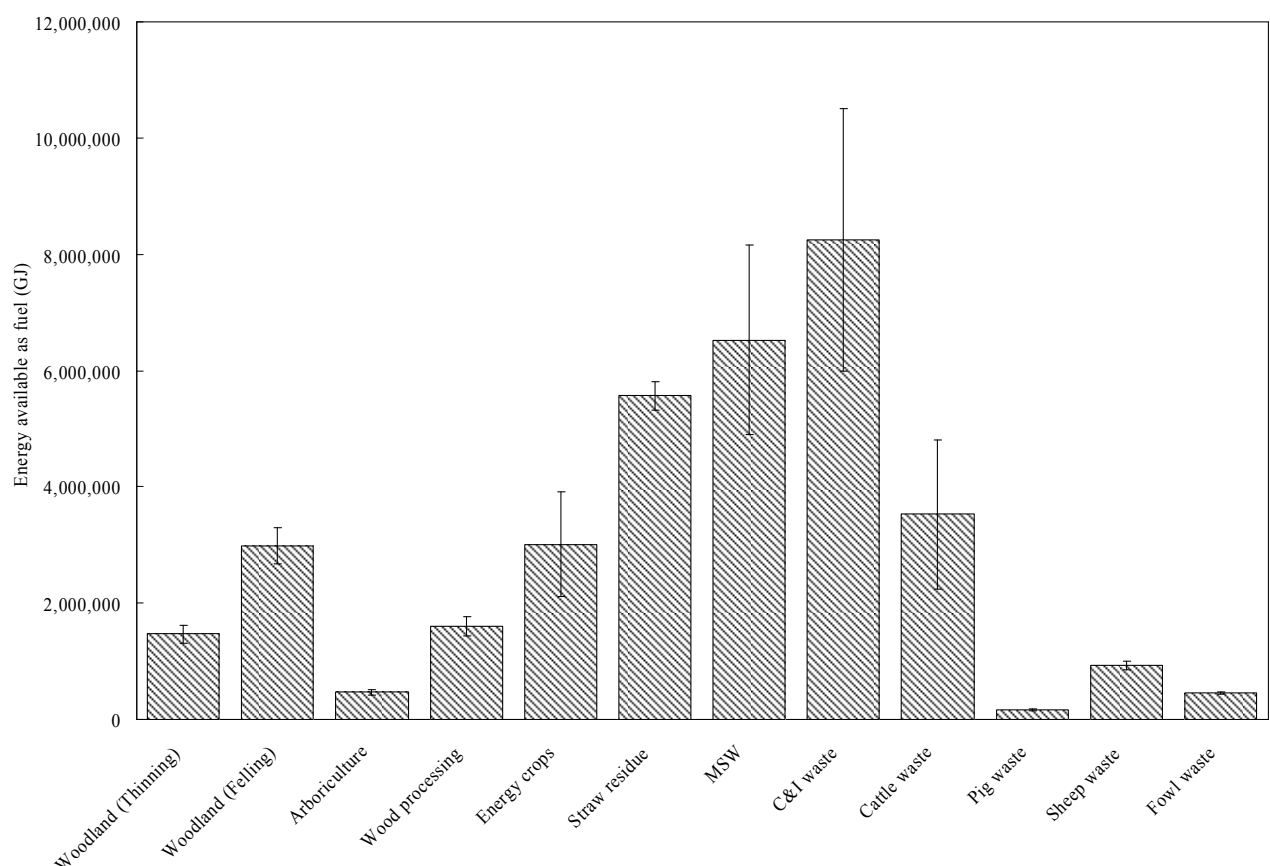


Figure 3-9 Resource Assessment B - Current potential bioenergy availability

One of the highest resources available within the region was found to be straw. Straw is a by-product of wheat, barley, oats and rye production. The main source of straw in the South West is from wheat and barley, which is produced from over a quarter of a million hectares within

the region. Straw is currently used within the farming sector as follows: 40% is ploughed back into land to improve soil fertility and structure, 30% baled for farmers own use and 30% sold by farmers (Nix 2003). Other reports suggest that around 45% of total straw produced in the UK is either burnt or ploughed back into fields (Ekman et al. 1998). Following the launch of the Crop Residue Burning Regulations, straw burning post harvest has been banned (Lynch & Schepers 2008). Straw availability is dependant on wheat production and therefore may fluctuate from year to year. Additionally the use of straw for bioenergy would have implications on animal bedding and fertiliser availability. Consequently this route could have indirect costs associated to it.

The UK is reported to produce over 15 million tonnes of straw per year. According to work carried out by the Department for Business, Enterprise and Regulatory Reform, 50% of this could feasibly be used for energy production (BERR 2003). Within this assessment, a target of 30% straw-to-bioenergy uptake was envisaged. This was considered suitable as it equalled the quantity available for farmers for own use. In reality this figure would be derived from all three straw supply chains. Using the assumption of 30% regional straw intake for bioenergy, resulted in 6 million GJ_{NCV}/year of energy potential. This value accounts for straw cultivated from wheat and barley, using a straw production constant of 4.5 tonnes/ha.

Another abundant biomass resource found in the assessment was derived from non-farm waste. This source of energy accounted for nearly 30% of the potential supply for bioenergy in the region. Municipal and solid waste (MSW) and Commercial & Industrial (C&I) wastes were found to offer between 9 million to 13 million GJ_{NCV} annually, based on available resources (DEFRA 2007a; South West Regional Assembly 2004). The calculation assumed that only wastes entering landfill would be converted into energy. Additionally the net calorific value for waste ranged between 3 GJ/tonne and 6.7 GJ/tonne depending on the organic matter content. As these wastes are not completely from renewable resources it is questionable whether they should be considered as a bioenergy. There is a significant drive to minimise waste and therefore the abundance of this resource should not be the focus of this resource assessment.

A Regional Waste Strategy was published in 2004 which underlined the necessity for effective waste minimisation (South West Regional Assembly 2004). Various policies were also implemented aiming to reduce waste generation in the region. Landfill Tax, packaging regulations and the Waste and Emissions Trading Act 2003 contributed to the reduction of waste generation. This could therefore, potentially reduce the availability of bioenergy from waste sources (BERR 2007c).

Other sources of available bioenergy included dedicated energy crops grown on set-aside land such as miscanthus and short rotation coppice (SRC). Only miscanthus and SRC for both set-aside and non set-aside land were considered due to the availability of data (H. Hout, DEFRA data centre, 04/03/2008, personal communication). Energy crops were calculated to produce up to 3 million GJ_{NCV} annually using the land currently allocated to bioenergy in the region. In 2007 however, energy crops on non set-aside land greatly outweighed crops grown on set-aside, as farmers were able to choose which land provides the greatest return on their investment.

Energy crops grown on arable land could become more common within the region as farmers are able to obtain competitive annual returns for energy crops as well as food crops (DEFRA 2008a). In 2005, the Common Agricultural Policy (CAP) was reformed and all individual payment schemes were replaced with one single payment with more focus on land stewardship. This aimed for farmers to grow a greater choice of crops based on the highest annual return, thus opening up the potential to use land for energy crop purposes (DEFRA 2008a). Energy crop grants can be beneficial for crops such as miscanthus and SRC to be economically viable.

Energy from farm-animal waste could provide a significant portion of the bioenergy mix. Cattle waste was found to contribute the highest (around 4 million GJ_{NCV}/year) of all farm wastes. Farm waste calculations adopted standard feedstock availability per animal of 50% per year. This factored in the lack of manure collection during summer periods when animals are grazing. Additionally, only 20% of the total livestock population was accounted for, in accordance with other regional estimates (Capener et al. 2005). This was considered suitable for currently available animal manure as it posed possibly very few infrastructural changes to farmers.

In contrast with current bioenergy production, shown in assessment A, woodfuel was found to have a much higher contribution. Approximately 463,382 ODT of biomass wood per year was determined as being potentially available as biomass. This included all stemwood, tips, branches, foliage and poor quality wood. However, of this total, 330,000 ODT was currently already marketed for other timber products and was considered unlikely to be used as bioenergy (Forestry Commission 2007). Therefore the largest woodfuel resource type was arboriculture arisings, followed by small roundwood and branch wood from forestry (McKay 2006).

The calculated bioenergy resource availability in the South West was estimated to be between 28 million GJ_{NCV} to 49 million GJ_{NCV} per year. This was found to contribute between 2.6-5.5% of the region's primary energy use. When assessing the maximum theoretical bioenergy resource, the increase of the available potential was a result of relatively straightforward changes to market re-allocation. For example, straw use and animal waste management was altered in coherence with recent Governmental strategies (BERR 2007c) and similar regional resource assessments (Capener et al. 2005), as opposed to reducing food production and creating competition for land use. Therefore, as the data shows, current bioenergy production in the South West could be increased significantly, without the increase of new biomass production. However, there are uncertainties in the economic and environmental impacts associated with these changes.

3.4.3 Resource assessment C

Analysis of the South West's future bioenergy potential as displayed in Fig 3-10, showed increases amongst some areas of resource, whilst a decrease in others. Overall, there was an increase in future bioenergy resources, compared to currently available resources. The analysis considered up to 2020, as data predictions and forecasts were available for this timescale. Studies such as RE-vision 2020 (Capener et al. 2005), Rubbish to Resource (South West Regional Assembly 2004) and Stepping Forward Reports (Chambers et al. 2005) had all set targets for 2020. This also linked to the Government's plans to cut carbon emissions by 80%

by 2050 with real progress by 2020 (BERR 2007a). The third analysis examined the potential bioenergy available from biomass feedstocks within the region, using forecasts of land-use, waste management and woodland use (Capener et al. 2005; Chambers et al. 2005; South West Regional Assembly 2004).

The analysis showed that bioenergy potential could be as high 54 million GJ_{NCV} per year. The bioenergy potential increased further from the second analysis due to the maximisation of animal waste and exploiting energy crops grown on arable land; considered suitable for bioenergy crop growth (Hammond et al. 2008b). Other land suitable for biomass was grassland under five years of age (Hammond et al. 2008b). This type of grassland accounted for over 200,000 ha, more than four times the land-area allocated in 2007 for set-aside use. Although set-aside land in 2008 was set to 0%, it was made clear that the decision would only be taken for 2008 (DEFRA Observatory 2008). Surveys carried out in the early part of 2008 estimated that only 40% of set-aside land and bare fallow land would be used by farmers, leaving the rest un-cropped (DEFRA 2008b; Upham & Shackley 2006).

By eliminating set-aside land, thus increasing the available land for farm-use, a driver was created for farmers to grow more profitable energy crops as well as food crops. However, the high wheat prices recorded for 2007-2008, peaking at just under £180/tonne resulted in farmers growing wheat for food rather than energy crops. This study concluded that energy crops could be grown on a land area equivalent to that of set-aside land during 2006-2007, approximately 57,000 ha. This accounted for less than 2.7% of total farmed land for the region. The change in total farmed area from 2002 to 2006 increased by 112,000 ha alone; therefore a bioenergy uptake of 57,000 ha was considered not to have serious impacts on current farming land use within the region.

Findings also showed that although there was a lower contribution from MSW and C&I waste, overall bioenergy potential was still higher than current maximum potential. This highlighted the region's potential of moving away from 'uncontrolled' sources of bioenergy such as waste generation, to a more 'controlled' production, such as energy crops. This suggested that the region has the capability of producing bioenergy from controlled direct sources, rather than a secondary use such as the recovery of energy from waste. Dedicated energy crops and managed woodland are imperative in supplying consistent bioenergy resources, as they will also maintain a steady source of resource material.

The analysis highlighted that the bioenergy dependence on waste could gradually reduce, as shown in Figure 3-10. It was assumed MSW and C&I would be reduced due to increased recycling and stringent regulations posed on landfill sites (South West Regional Assembly 2004). The combined energy available from MSW and C&I was found to be 7 million GJ_{NCV} per year. Compared to the current availability of energy from MSW and C&I (9-12 million GJ_{NCV}) this was reduced. The region's Waste Strategy, states that by "2030 the region will become a minimum waste producer" (South West Regional Assembly 2004) and confirms the proposals to reduce waste. Meanwhile, bioenergy from woodfuel in the South West was calculated to remain constant until 2021 (Forestry Commission 2007). Predictions from the Forestry Commission studies showed that there would be little or no increase in available woodfuel biomass until 2021 (Forestry Commission 2007).

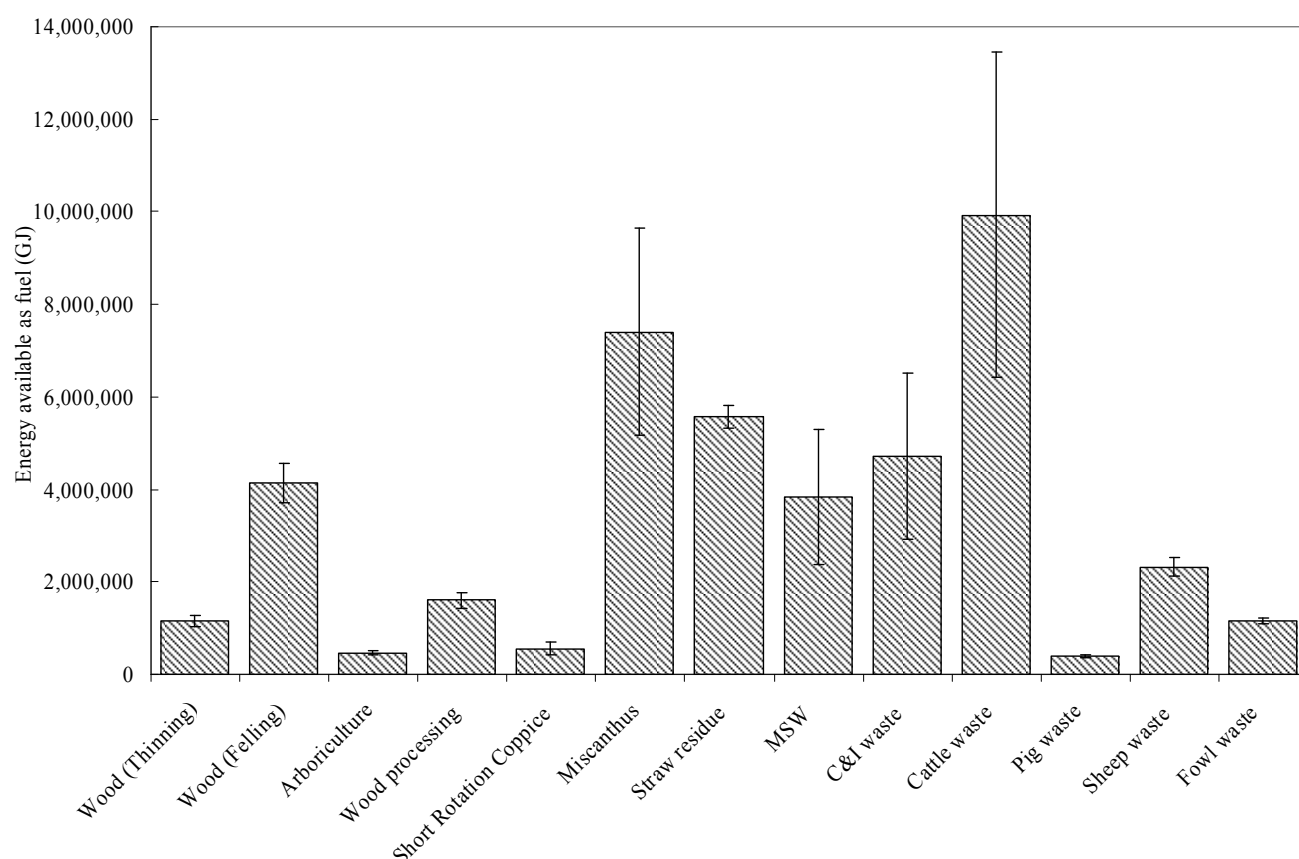


Figure 3-10 Resource assessment C - Future potential bioenergy availability (estimated for 2020)

The bioenergy potential of animal waste was calculated using a double of the theoretical waste intake used in the previous assessment. This equated to 40% of total animal waste (assuming again a standard 50% annual collection of the actual waste). This figure would result in a 2% increase in uptake per year up to 2020, which was considered a potentially suitable scenario. Overall it was calculated that farm waste could realistically contribute to nearly half of the region's bioenergy supply. The resource assessment highlighted the large potential of energy from farm waste within the region.

3.5 Brief analysis of results

The findings showed that future bioenergy potential for the South West could be increased over a range of bioenergy feedstocks whilst MSW and C&I wastes were estimated to reduce. Given the stable animal farming population over the past 7 years, the main increased future supply of bioenergy relied on maximising usage of arable land and exploiting the use of existing farm waste. A comparative table (Table 3-3) highlights the increase between the three resources assessments.

	Annual bioenergy availability GJ _{NCV}	
	Minimum	Maximum
Resource Assessment A	3,865,000	5,292,000
Resource Assessment B	28,700,000	49,640,000
Resource Assessment C	32,782,000	53,699,000

Table 3-3 Maximum and minimum contribution of bioenergy for each resource assessment

Another key element to the increase in bioenergy potential was linked to the utilization of arable land. The use of this particular land was assumed to produce miscanthus. In reality, the land could be used for any other energy crops or a mixture of crops. The choice of miscanthus in this analysis was to maximise the available energy as a fuel from the biomass resource. In a commercial environment, farmers will probably choose the optimum land-use based on maximum financial return. As a result land for energy crops may be diverse or monoculture depending on the particular demand in the future.

One of the key contributions towards bioenergy resources in the South West was animal waste. Resource assessment B assumed an uptake of 20% inline with similar resource assessments, whilst assessment C envisaged a 40% uptake by 2020. Using these relatively low uptake assumptions proved a considerable bioenergy potential for the region. In the UK, manures have high moisture concentrations (over 80% generally) and therefore are not considered suitable for direct combustion. The use of anaerobic digestion for biogas production is often used to extract energy from this resource.

Total manure production for the UK in 2005 was estimated to be around 88 million tonnes, 30% of which is liquid slurry (Mistry & Misselbrook 2005). Liquid slurry is considered as an ideal feedstock for biogas production from anaerobic digestion. A combination of farm waste and industry food waste is often utilised, as non-farm waste provides additional income through increased biogas yields. However biogas generation can also be amplified through the addition of energy crops during the digestion process. As a result, the arable land available in the South West could be used to aid the production of biogas.

The study found significant benefits of adopting an increase uptake of animal waste for the production of biogas. Currently animal manure is ploughed directly back into fields as a form of natural fertiliser. However, the digestate from anaerobic digestion of animal waste is suitable as a fertiliser and in some cases has advantages over undigested slurries and manure as it offers a consistent nutrient concentration (DEFRA 2007c). Theoretically a scenario of 100% adoption of animal waste for biogas production could be considered if AD plants were to become economically feasible, through grants or funding. However this would be unrealistic as the collection and distribution of the waste could have a detrimental impact on road transport. Nevertheless, biogas production from anaerobic digestion was considered a suitable conversion process for the South West region due to:

- The majority of current energy from waste in the South West region is collected through biogas production and generally is the most used form of energy recovery from waste;
- The use of biogas from farm waste enables the waste to be used as a natural source of fertiliser, thus not affecting current end use of manures;
- Biogas is considered a renewable energy source and is defined as a primary fuel according to the Digest of United Kingdom Energy Statistics (BERR 2008a).

3.6 Summary

The resource assessment showed that biomass resources currently utilised were considerably fewer than the current available biomass. Current biomass resources were found to originate from waste, from either landfill gas or incineration. It was observed that the bioenergy shift

could move towards perennial and improved farm manure management as these two biomass branches offered greater economic returns than energy recovery from waste in the future. Municipal and other non-farm waste types were also estimated to become more stringent in terms of availability. The region's abundant resources of biomass showed that technological development could be advanced. Economic constraints ought to, according to the UK Biomass Strategy, pose fewer issues due to funding mechanisms currently available.

It can be concluded that slow development of the bioenergy sector was not dependant on biomass resource availability. The results showed that the South West does have extensive arable land availability and optimum climatic conditions for bioenergy feedstocks. However, the slow uptake of bioenergy technologies has resulted in low stimulation for the bioenergy feedstock growth and supply.

Overall, the resource assessment envisaged the use of anaerobic digestion (AD) for biogas production as a suitable bioenergy pathway. This complemented the abundance of resource required for this technology, but was also considered a plausible route in merging the availability of arable land and the recovery of energy from waste.

A detailed discussion of these results has been shown in Chapter 10, where it is contextualised with the drivers and barriers to bioenergy development for the UK, using specific case studies from the South West of England. Resource assessment B and C have been discussed further, whilst Resource assessment A should be used to signify the current lack of bioenergy uptake.

4 BARRIERS AND DRIVERS TO BIOENERGY DEVELOPMENT

4.1 *Introduction*

The previous chapter highlighted the resource availability for bioenergy development in the South West of England. However the use of bioenergy in the region (reflected by the UK as a whole) has been limited and the uptake of new bioenergy projects is slow (Adams et al. 2008). This chapter examines the potential barriers affecting bioenergy development within the UK, whilst also exploring some of the key drivers for this energy source. The research undertaken within this particular study is also a tool for addressing the opportunities and weaknesses of bioenergy development as a whole.

The work was jointly undertaken between the lead authors Mezzullo, W. and Adams, P. (Adams et al. 2008). The research was presented in December 2008 at the Biomass and Energy Crops III conference (Adams et al. 2008). The work has been expanded, updated and reported within this chapter. The publication has been attached in Appendix D.

4.1.1 **Background and scope**

Biomass has been embraced as a fundamental part of reducing carbon emissions in the UK. Over the current decade there has been a noticeable drive to increase the use of bioenergy. One of the first major bioenergy Government reports was published in 2005 (Gill et al. 2005) which highlighted the need to secure a strong biomass supply chain from harvest to delivery of the energy.

Increasing the development of bioenergy has been planned through a series of policies, legislative changes and financial support mechanisms. The overarching policy driver was a series of Energy White papers (BERR 2007a) and the UK Biomass Strategy (BERR 2007b). Other policy drivers included Government-set regulations to directly increase the use of biomass. These drivers were implemented through the Renewable Obligation scheme (RO), an incentive to promote the use of renewable energy for electricity production. The RO scheme creates an obligation for UK electricity suppliers to source just under 10% of electricity from renewable sources. In addition to this, feed-in-tariffs (FIT) have also been newly introduced. These act as a secured additional income for electricity production from renewable energy resources which are guaranteed over a period of time (Ofgem 2010). Although there are currently no financial drivers for renewable heat generation, the Government is considering the introduction of a dedicated renewable heat incentive (BERR 2008b).

Within the transport sector, similar policies also exist. In April 2008, the Renewable Transport Fuel Obligation (RTFO) was launched with a target for 3.25% of road transport fuel (by volume) should be obtained from renewable sources by 2010 (RFA 2009). The scheme works parallel with the European Union Directive on Biofuels (Adams et al. 2008; RFA 2009).

The envisaged progress of bioenergy development by policy does not appear to have materialised. In recent times 2.3% of the UK's electricity is generated from biomass sources, whilst bioenergy contributes a further 1% towards heat and transport (Adams et al. 2008). It is apparent therefore, that bioenergy has not advanced to forecasted or desirable levels.

The work detailed in this chapter examines the reasons for the low bioenergy uptake in the UK, with a particular focus on the South West of England. The research aimed to understand the “barriers” that may be hindering the progress of bioenergy. An understanding of the critical barriers was required to determine the areas in which bioenergy is failing across the supply chain. Links were established between bioenergy experiences on a regional and national level.

A literature analysis highlighted a number of unsuccessful attempts of bioenergy in UK. In 2005 for example, 15 out of the 22 proposed biomass electricity plants failed to operate (van der Horst 2005). Other examples included various failed bioenergy attempts in the South West, which are analysed and discussed in later sections. Commonalities existed in the barriers affecting the bioenergy projects and these were considered as a key reason for the overall slow-growth of bioenergy. The aim of this chapter is to understand what may have been the causes contributing towards these failed bioenergy attempts.

In addition to examining the barriers to bioenergy development, the drivers to development were also analysed to understand the links between the two. A series of barriers and drivers were proposed from the literature review and validated through the use of a questionnaire to relevant stakeholder groups. From the questionnaire the barriers and driver were ranked in order of criticality.

4.2 Bioenergy experiences from the South West

In 2004, the Government Office for the South West (GOSW) commissioned a report examining the potential of renewable energy for the South West. It concluded that the region could produce between 11-15% of its electricity from renewable energy sources by 2010 (RegenSW 2003). However, no regional targets were set for transport or heat energy. The South West’s current renewable energy production has an installed capacity of 150MW (RegenSW 2008). Previous work carried out by Hammond et al. (2008a) calculated the actual biomass feedstock used in the South West was between 170MW-250MW of installed capacity. This was significantly higher and largely due to the region’s landfill energy recovery systems, providing over 450GWh of energy per year (Hammond et al. 2008a).

It is estimated that only around 1% of the region’s total energy consumption for heat and power is derived from renewable sources (RegenSW 2008). This is mirrored throughout the whole of the UK, where total renewable energy did not exceed more than 50 TWh production in 2008 (total UK renewable heat energy consumption in that year was around 2,800 TWh) (BERR 2008a;HM Government 2009).

4.2.1 Current bioenergy projects in the South West

In 2004, the Government awarded £18m of funds to five bioenergy plants across the UK (HM Government 2007). The combined capacity of these plants was 39MW_e using a mixture of wood and energy crops (Thornley 2006). Four out of the five projects (total of £17.5m) were awarded to plants within the South West of England. To date, none of the projects in the South West of England are fully operational (RegenSW 2008). Studies carried out on some of the projects concluded a number of key reasons for unsuccessful biomass developments. Some of these projects have been analysed in the following section.

Winkleigh 21.5MW_e gasification plant

In 2001, a plan was outlined to design, develop and install a gasification plant in the town of Winkleigh in Devon, UK. The total cost of the gasification plant was predicted to be £37million. However, due to local opposition the decision to implement the plant was overturned. A survey carried out in 2004 highlighted that 88% of the local community felt negatively regarding the installation of the plant (Upham & Shackley 2006). The same study also showed there was a significant mistrust between the local community, developers and agencies involved. According to Upham & Shackley (2006), local people believed the plant had been falsely advertised through the media. Other issues included the location of the plant which created issues with residents living near-by and the increased use of local roads which could have detrimental environmental impacts (McCormick & Kaberger 2007).

North Wiltshire biomass plant 5.5MW_e

In May 2000, planning applications for a wood gasification plant was submitted to the North Wiltshire District Council. The plant was designed to use up to 36,000 oven dry tonnes of wood collected within a radius of 30 miles (Upreti & van der Horst 2004). The plant was estimated to create 83 permanent jobs in the area (Upreti & van der Horst 2004). The plans received opposition and the community initiated a campaign called “Biomass Lumbered on Our Town” (BLOT) to oppose the biomass site. The plans were then terminated on the grounds of significant visual harm (Upreti 2004).

Green Spirit Fuels Ltd, bioethanol manufacturer

Launched in 2005, the company was created to produce bioethanol for road transport in Somerset. This plant was designed to produce 130million litres of bioethanol per year. The project secured planning permission in January 2006 and building was intended to commence in January 2007. However after a press release in June 2008, it is understood that due to funding issues construction has not yet commenced (GSF 2008).

Other biomass projects in the South West

Roves Energy was granted £0.96million to build a combined heat and power plant (CHP), fuelled by 5000ha of local energy crops in Swindon (HM Government 2007;Thornley 2006). The plant was to adopt an electricity generating technology capable of producing 2MW_e. The fund was granted in 2004 but has not yet been built.

Another CHP plant project was initially set up in 2003 in Somerset. The plant was to produce 6.9MW_e and 1.5MW_t. The project was successfully granted £3.8million of funding for the development of the plant. The plant however experienced technical difficulties leading to substantial financial challenges. Eventually the plant was closed permanently due to undisclosed technology issues associated with the gasification process (Boyle 2004).

4.2.2 Observed issues with bioenergy development

Bioenergy’s lacklustre growth in the region can be associated with a number of barriers. These barriers are not uncommon in other regions of the UK and in other countries. Several studies concluded there is a pattern to the barriers which impede the development of bioenergy (Roos et al. 1999;Upham & Shackley 2006;Upreti 2004;Upreti & van der Horst 2004). These barriers to bioenergy can be divided into two categories; technical and non-technical challenges (Rosch &

Kaltschmitt 1999). This determines whether the actual plant operability is an issue or whether challenges arise from outside factors.

Technical barriers are generally related to modern, often commercially unproven technologies, which have yet to become economically viable. An example of this is the conversion of solid biomass to liquid biofuels, also known as 2nd generation biofuels. Due to the advanced conversion technology adopted, these plants are estimated to cost around 4 times the amount of conventional 1st generation biofuel plants and around 2-3 times the cost of producing fossil-fuel oil derived diesel or petrol (Kavalov & Peteves 2005). Other technical barriers can emerge from developments not meeting environmental regulations or quality standards. Operational activities of the plant can also encounter technical issues which lead to financial complications or ultimately in plant shut down.

Non-technical barriers govern all the other aspects in which a bioenergy plant may experience difficulties. This includes lack of feedstock availability and other financial issues such as administrative costs. Perceptual challenges can also hinder the development of bioenergy plants, which is clearly seen with some of the case studies above. The ultimate end-user request for bioenergy can also vary, subsequently affecting the outcome and success of a bioenergy plant. Literature shows that within the UK and in particular the South West, the main barriers to bioenergy projects included:

- Location of bioenergy plant – visual impacts (Upham & Shackley 2006);
- Transport increase around bioenergy plant (Upreti 2004);
- Mistrust between local community, developers and agencies – credibility of developer (Upham & Shackley 2007; Upham & Shackley 2006);
- Other environmental impacts – odours emitting etc. (McCormick & Kaberger 2007);
- Financial implications during operation and lifespan of plant (Piterou et al. 2008);
- Technical problems associated with conversion techniques (Piterou et al. 2008). These technology issues can also include the practicality of installing district heating systems from biomass plants to end-users, situating a plant sufficiently close to an electrical grid feeder and minimising noise and odour emissions during the plant's operation.

From the literature analyses, it was apparent that barriers to the development of a bioenergy project differed at varying stages throughout the lifecycle of project implementation. A flowchart for a typical bioenergy project is shown Figure 4-1. It should be noted that although this flowchart represents the typical stakeholders of a bioenergy operation, there are some situations where the feedstock supplier, technology owner and end-user are all represented by one stakeholder.

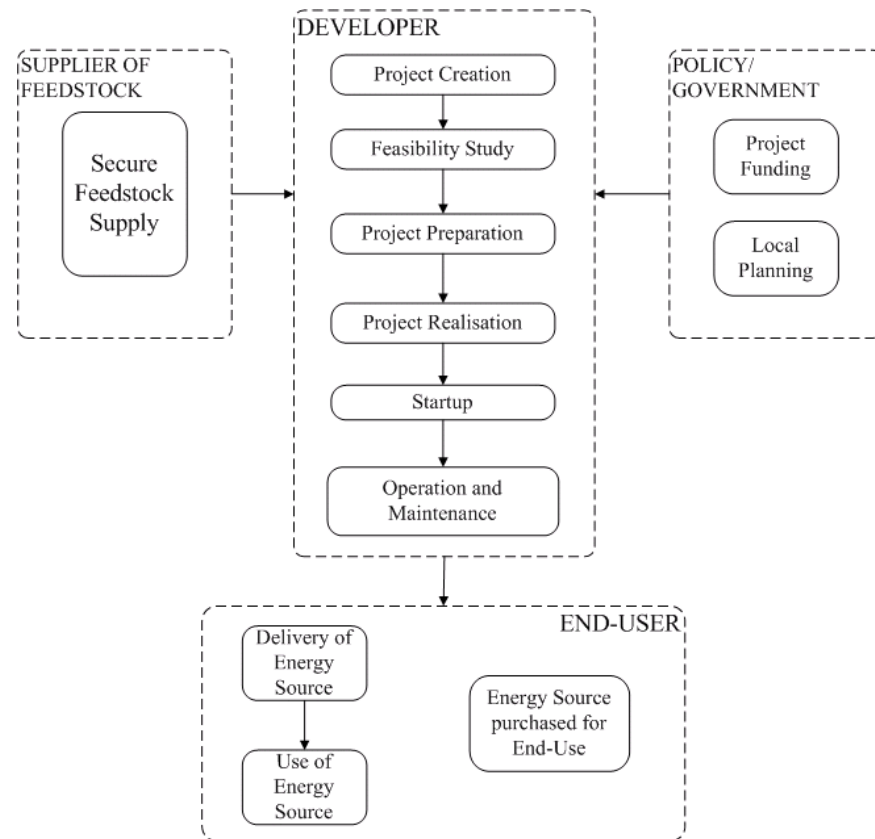


Figure 4-1 Linkage between stakeholders groups for bioenergy projects – (Adams et al. 2008)

The development of a bioenergy project can be affected by a number of externalities outside of the developer's control, shown in Figure 4-1. These externalities, along with the developer's inputs can be categorized into four groups: farmer/supplier of feedstock, developer and user of plant, policy/government input and end-user of bioenergy. Although there are many other factors that affect the development of a bioenergy project, such as the effects on the local community and the contribution from external investors, it was assumed that these four areas represented a supply chain to bioenergy development projects.

4.3 Methodology for identifying barriers and drivers to bioenergy development

The root causes for unsuccessful bioenergy projects can originate from any or multiple stages of the project's development chain. The supply chain, considered a critical part of the success of a bioenergy development (Gill et al. 2005), is ultimately created between the demand for bioenergy and the supply of the energy source.

The demand from the end-user is stimulated mainly by governmental support such as mechanisms put in place to develop the market (Gill et al. 2005). These mechanisms can also be applied to bioenergy feedstock supply. To date, there are a range of mechanisms implemented within the UK to support the development of biomass production. In order to identify the barriers to bioenergy development it was necessary to understand whether barriers differed throughout the supply chain. In addition, the drivers were also analysed at each stage of the bioenergy supply chain to determine the possible links between barriers and

drivers for each stage. After identifying the four key stakeholders of a successful bioenergy development, they were subsequently defined:

Farmer/supplier of feedstock

This group is involved in growing, collecting and overall production of feedstock for a biomass plant. The study covered all aspects of bioenergy including biofuels, heat from biomass and electricity from biomass. Therefore all potential feedstocks were considered. These included (Hammond et al. 2008b):

- Arable/Annual Crops – Oilseed rape, wheat, sugar beet etc;
- Herbaceous Crops – Miscanthus, switch grass, reed canary grass;
- Woody Perennials – Short rotation coppice (SRC), pine/spruce;
- Residues and Waste – Forest residue, farm waste, organic municipal waste, organic industry/other waste.

Plant developer/owner

These stakeholders are involved in developing the biomass plant. This included building/design and feasibility consultants, engineers, financiers and plant owners. Types of biomass plants included: biodiesel production plants, bioethanol production plants, biomass combined heat and power (CHP) plants, gasification plants, other biomass electricity, biomass heat, anaerobic digestion plants and other waste treatment with energy recovery systems.

Government/policy

This stakeholder group included governmental organisations, agencies and local authorities. Organisations which lobbied the Government to try and influence bioenergy policy were also included. These stakeholders were interested in bioenergy development from a legislative standpoint.

Primary bioenergy end-user

This group represented the primary end-user or purchaser of bioenergy. This did not include the effective end-user of the bioenergy. For example, a vehicle fuel supplier was considered an end-user, rather than a road user purchasing the fuel at a forecourt. It was assumed that primary end-users would qualify as major stakeholders rather than actual users of the bioenergy. Other examples included electricity suppliers which purchase electricity generated from biomass. These were considered as end-users as their drivers for biomass electricity would be more related to the study than the drivers of the actual end-user of the electricity.

4.3.1 Linking the bioenergy stakeholder groups

Barriers to bioenergy development are likely to differ between the four stakeholder groups because of different drivers associated with each group. For example, a driver for government/policy may be to pursue bioenergy development to help reduce carbon emissions; however, for a plant developer/owner this driver may not be as important. These links between the four stakeholder groups need to be understood in order to determine the most important barriers to the development of bioenergy.

Bioenergy as a whole was examined through the four stakeholder groups. This included all feedstocks, conversion techniques and end-uses. It was acknowledged that there were a large number of bioenergy 'pathways' and that potentially the barriers and drivers for each pathway could be different. For example, growing and supplying miscanthus would require different sowing, growing and harvesting techniques compared to annual crops such as maize and wheat. Additionally this type of feedstock would be very different to supplying waste by-product feedstocks such as manure. This could therefore, pose barriers to suppliers who wish to supply different feedstocks.

Having acknowledged each bioenergy pathway could have different associated barriers and drivers, the study focused on more overarching aspects of development as opposed to individual situations. It was acknowledged that identifying specific barriers for each bioenergy pathway would narrow the scope of the research and thus would be outside the remit of the study. Additionally, the research was intended to review the barriers and drivers with a holistic approach in support of Government bioenergy strategies (BERR 2007b; Gill et al. 2005). This work clarified the common barriers and drivers throughout all bioenergy pathways.

The bioenergy pathways as shown earlier in Figure 2-3 demonstrate three of the four stakeholder groups that are responsible for the development of bioenergy. It was recognised that governmental influence was the overarching influence over the three stages of the bioenergy supply chain. From this analogy a simplified schematic of the link between the three stakeholder groups and the overarching influence of government/policy has been displayed in Figure 4-2.

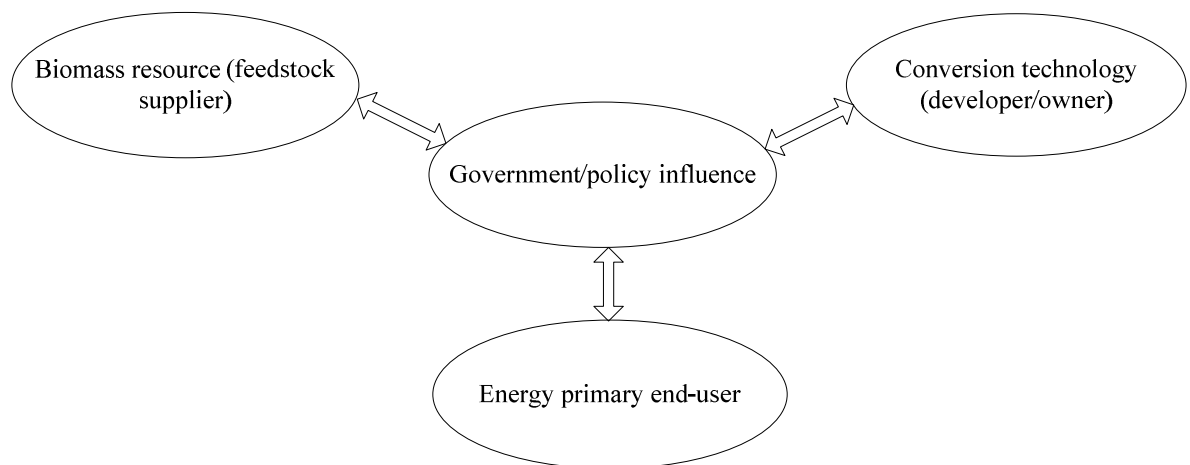


Figure 4-2 Governmental/policy influence on biomass supply chain

The study proposed a list of possible barriers and drivers to the development, use and support of bioenergy for the four different stakeholder groups. The barriers proposed resulted from an extensive literature review and analysis of case studies. To understand the routes of these barriers, the bioenergy development drivers were also proposed. It was acknowledged that other drivers and barriers may be associated with bioenergy development. The study investigated the validity of these barriers and drivers for each stakeholder within bioenergy supply chain. Each barrier was then analysed to determine the implications it could have on the implementation of bioenergy.

4.3.2 Drivers and barriers for feedstock suppliers

Suppliers of feedstock were partly considered to be farmers able to supply bioenergy crops. Other feedstock suppliers included waste suppliers, such as tree surgeons or sawmills. Similarly, organic waste suppliers were also included as these could supply feedstock either for anaerobic digestion, gasification or incineration. There could be a number of drivers for the supply of bioenergy feedstock, but due to a number of challenges, there were also several barriers which could discourage bioenergy feedstock suppliers, as detailed in Table 4-1.

	Barriers	Drivers
Feedstock Supplier	A - Competition vs. other investments	K - Attractiveness of a growing bioenergy market
	B - Lack of feedstock experience	L - Availability of financial support
	C - Limited/uncertain return on investment	M - Market diversification
	D - Negative environmental impacts of feedstock	N - Meeting governmental targets
	E - Perceptual challenges of feedstock	O - Other environmental benefits (other than CO ₂ reduction)
	F - Physical resource limitation (i.e. land availability)	P - Possible reduction in carbon emissions
	G - Resource intensive feedstock	Q - Profitable return on investment
	H - Uncertainties of financial support	R - Reduction in fossil-based fuels
	I - Unclear legislative limitations	
	J - Unsettled bioenergy market (unreliable buyer)	

Table 4-1 Proposed barriers and drivers to the development of bioenergy for feedstock suppliers

There could be a perceived difficulty growing crops for either biofuels (Mattison & Norris 2007) or other bioenergy fuels instead of other food crops. These issues could arise from unfamiliar sowing, growing and harvesting techniques, diverse farming equipment requirements or land suitability. However farmers may be willing to overcome these issues as bioenergy could offer a diverse market either from previously grown crops or as an alternative use of farming by-products. Low or uncertain return on investment may be seen as an important barrier to the development of bioenergy feedstock (Sherrington et al. 2008). Uncertainties of grant or funding support could also be a potential barrier to bioenergy feedstock. Studies have shown that without financial support the uptake of bioenergy crop production would have been considerably lower (Sherrington et al. 2008). Additionally, locking farmers into long term contracts to supply crops such as miscanthus and SRC could also be seen as a barrier to feedstock suppliers. However this sole issue could be represented as competition vs. other investments and limited/uncertain return on investment.

Environmental implications associated with the supply of bioenergy feedstocks were also thought as potentially pivotal to supply of feedstock. A potential barrier proposed was the uncertain environmental effects of bioenergy feedstock production. Biodiversity effects of bioenergy monocultures could drive farmers or landowners away from producing feedstocks. In contrast, the belief of environmental benefits through adopting bioenergy could also be a driver for suppliers. Possible reductions in carbon emissions and a decreased dependence on fossil-based fuels further down the supply chain could also be drivers for bioenergy.

4.3.3 Drivers and barriers for bioenergy plant developers/owners

A key proposed barrier for this stakeholder group included adopting a conversion technology that could either be financially or practically unproven (Table 4-2). This was considered valid

across the board of bioenergy pathways. The production of biofuels for example could be faced with financially unproven or elevated costs of 2nd generation biofuel conversion techniques. Meanwhile, for heat production from bioenergy the costs and feasibility of implementing district heating systems could be seen as a barrier to the use of such technology.

	Barriers	Drivers
Plant Developer/Owner	A - Competition vs. other renewable energy options	J - Availability of financial reward/support mechanisms
	B - Lack of feedstock supply	K - Bioenergy supply consistency vs. other intermittent energy options
	C - Low primary-end-user demand	L - Bioenergy use versatility
	D - Perceptual challenges of bioenergy plant	M - Increase bioenergy interest from end-user
	E - Planning and installation issues	N - Market diversification/opportunity
	F - Possible negative environmental impacts	O - Possible reduction in carbon emissions
	G - Uncertain development and operational costs	P - Reduction in fossil-based fuels
	H - Uncertainty of conversion technology/equipment	Q - Variety of feedstock use for bioenergy.
	I - Unclear and complex legislative issues	Resource diversification

Table 4-2 Proposed barriers and drivers to the development of bioenergy for plant developers/owners

Other barriers that could hinder the development of bioenergy projects included a lack of local supply of feedstock, forcing developers to import biofuels from outside the UK. The import of wood-pellets into the UK signifies the lack of feedstock supply within the country (Junginger et al. 2008). However, the diverse range of feedstocks available for bioenergy is an attraction to the use of bioenergy. Financial considerations also offered a number of potential drivers and barriers to the development of bioenergy projects. Proposed drivers for bioenergy included Government support mechanisms, such as the bio-energy capital grant schemes and also the capability of bioenergy to produce financial rewards such as ROC and FIT. However uncertain financial costs associated with operation, maintenance of bioenergy plants and costs of bioenergy distribution were also anticipated to be a significant barrier (Piterou et al. 2008).

4.3.4 Drivers and barriers for primary end-users of bioenergy

	Barriers	Drivers
Primary End-User	A - Bioenergy costs vs. fossil-fuel	J - Ability to penetrate most energy markets
	B - Infrastructure and other costs	K - Bioenergy use consistency vs. other intermittent energy options
	C - Legislative issues	L - Direct substitute of fossil-based fuels
	D - Low supply of bioenergy	M - Help in supporting Governmental schemes
	E - Perceptual challenges of bioenergy use	N - Investment opportunity into renewable energy
	F - Preferences of other renewable energy options	O - Positive effects on image and PR
	G - Seasonal effects of bioenergy supply	P - Possible reduction in carbon emissions
	H - Uncertainty of adaptability	Q - Reduction in fossil-based fuels
	I - Unsettled/changing bioenergy market	

Table 4-3 Proposed barriers and drivers to the development of bioenergy for primary end-users

The primary end-users of bioenergy were considered to include a wide range of users from electricity suppliers requiring ROCs and FIT, to domestic heating users wanting to reduce dependency on fossil-based fuels and improve environmental impacts associated with energy use. The barriers (Table 4-3) associated to this stakeholder group included financial implications of bioenergy, similar to other stakeholder groups. High buying costs of bioenergy with respect to other sources of fossil-fuel derived energy or even other renewable energy options could potentially discourage the buying of bioenergy. Similarly, uncertainties within the bioenergy market and seasonal variability of feedstock supply would ultimately create volatile buying costs for various types of bioenergy. A similar trend can be seen for wheat crop prices during the 3rd quarter of 2007, where wheat prices rose from £90/tonne in February 2007 to £180/tonne in September 2007 (ENAGRI 2007).

Other barriers proposed for end-users included the uncertainty of adaptability of bioenergy. This can be seen within the biodiesel supply chain, where a number of vehicle manufacturers do not allow the use of biodiesel in their engines due to uncertainty of engine performance and longevity. Legislative issues were proposed as a possible barrier for primary end-users of all bioenergy pathways. These include uncertainties associated with international standards on the use of renewable fuels in transport and lack of unclear reward mechanisms for the use of bioenergy; currently present in the UK for bio-heat.

Drivers associated with bioenergy use included the ability to penetrate most energy markets, including heat generation, power production and transport energy uses. This driver also led to the favourable use of bioenergy as a direct substitute to existing energy conversion techniques. For example, the use of biofuels as a direct replacement of petro-diesel and petro-gasoline could favour biofuels over other renewable energy options for transport. Other examples include the ability to use cleaned biogas (ultimately pure methane) pumped into national gas grid networks and used for domestic heating or cooking. The drivers however also led other potential barriers for the adoption of bioenergy. These included uncertainties regarding infrastructural costs for using bioenergy. For example, the costs for district heating set-ups would also have to be met by the end-user of bioenergy which could result in a barrier for the adoption of such a technique.

4.3.5 Drivers and barriers for government/policy

	Barriers	Drivers
Government/Policy	A - Competition vs. other renewable energy options B - Lack of feedstock supply resource availability C - Legislative issues regarding bioenergy D - Negative effects on food crop prices E - Negative global environmental impacts F - Negative local environmental impacts G - Perceptual challenges H - Uncertainty of conversion technology/equipment	I - Bioenergy supply consistency vs. other intermittent energy options J - Bioenergy use versatility K - Decentralisation of energy capability L - Increase rural development and economy M - Increased fuel security N - Possible reduction in carbon emissions O - Reduction in fossil-based fuels P - Variety of feedstock use for bioenergy. Resource diversification

Table 4-4 Proposed barriers and drivers to the development of bioenergy for Government/policy stakeholders

Table 4-4 shows the barriers and drivers affecting government/policy stakeholders, reflecting how this group would support the use and development of bioenergy. Proposed barriers included the uncertainty of financial support mechanisms which may be used on unproven conversion technologies that could ultimately not provide a valid return on investment. Support mechanisms may also be affected by the environmental benefits or detriments of bioenergy use. Recent reports question these benefits when considering biofuels for transport (EAC 2008;The Royal Society 2008).

Other barriers proposed for this stakeholder group include the competition that bioenergy could face versus other renewable energy options, such as wind energy or solar. This could have implications on obtaining suitable financial support for bioenergy developments. It was also suggested that barriers to bioenergy, from a government/policy perspective, could be seen as a link between bioenergy crop growth and the potential link to the rise in food crop prices. The effects of bioenergy on food crops may be viewed as a significant barrier to the development of bioenergy for these stakeholders. Lack of sustainable feedstock availability was also proposed as an important barrier for these stakeholders. Sourcing feedstock from unsustainable sources could have negative implications on the environmental benefits of using bioenergy, which could ultimately hinder government-set targets of carbon reductions, and increasing fuel security (BERR 2007a).

Drivers for the development of bioenergy were derived through a series of Governmental strategies (BERR 2007b). These strategies were proposed to develop all routes of bioenergy in order to meet governmental energy targets. These targets included: increasing energy security, reducing carbon emissions and reducing overall dependency on fossil fuels. Therefore, these drivers were seen as important factors from a government/policy perspective for the development of bioenergy. Parallel to these drivers are incentives for diversifying the use of waste. Reducing waste to landfill through the Landfill Directive encourages the use of biomass waste for energy purposes (DEFRA 2007d).

4.3.6 Stakeholder survey for barriers and drivers to bioenergy

Having proposed a number of barriers and drivers for each stakeholder group, a stakeholder survey was subsequently prepared to determine the importance of various barriers to bioenergy projects. The stakeholders for each group were obtained through a number of bioenergy-related events attended during 2007-2008. All bioenergy-related events, seminars, conferences and courses were addressed to all bioenergy fields, as opposed to single bioenergy pathways. This reinforced the methodology to treat bioenergy as a whole. Bioenergy related contacts via personal communications were also considered as suitable stakeholders for some of the groups. The stakeholder's suitability was assessed based on previous experience within the bioenergy field, or a relevant interest in bioenergy.

In order to survey the stakeholder groups, an online questionnaire was constructed. Stakeholders were asked how important each barrier and driver was for the development of bioenergy. The questionnaire offered the candidates five choices: critical importance, very important, moderate importance, unimportant or undecided. The respondents were also able to add additional barriers or drivers which they thought to be important in the development of bioenergy. The stakeholders were contacted via email with a covering document explaining the details of the research. The email enclosed a web link directing them to the online survey. Once the questionnaire was completed, the respondent submitted the information which was stored in an online database. The response rate of the survey was just over 45% with a total of 72 respondents. This averaged around 18 responses per stakeholder group. The stakeholders represented all bioenergy types and scales of bioenergy implementation. Screenshots of the online survey has been displayed in Appendix E.

4.4 Results

The results from the questionnaire highlighted the main drivers and barriers of critical/important significance. The technique adopted for displaying the results also highlighted the least important drivers and barriers. From these outcomes the possible links between barriers of different stakeholder groups were assessed to determine whether there were patterns or consistencies of barriers and drivers along the supply chain.

4.4.1 Farmers/suppliers stakeholders of bioenergy feedstocks

Critical barriers for the development of bioenergy feedstocks were predominantly the competition with other investments and the uncertainty of a return on investment. The latter was considered to either be critically important (50%) or very important (35%). However, around 25% of the stakeholders also mentioned the uncertainty of funding as being another critical barrier. Another significant barrier focused on the issue of physical resource availability, which could limit the generation and supply of bioenergy feedstocks. The least important barriers recognized by this stakeholder group included the effects on the environment of producing bioenergy feedstocks and the perceptual challenges, which could be faced; 36% and 48% respectively (low importance).

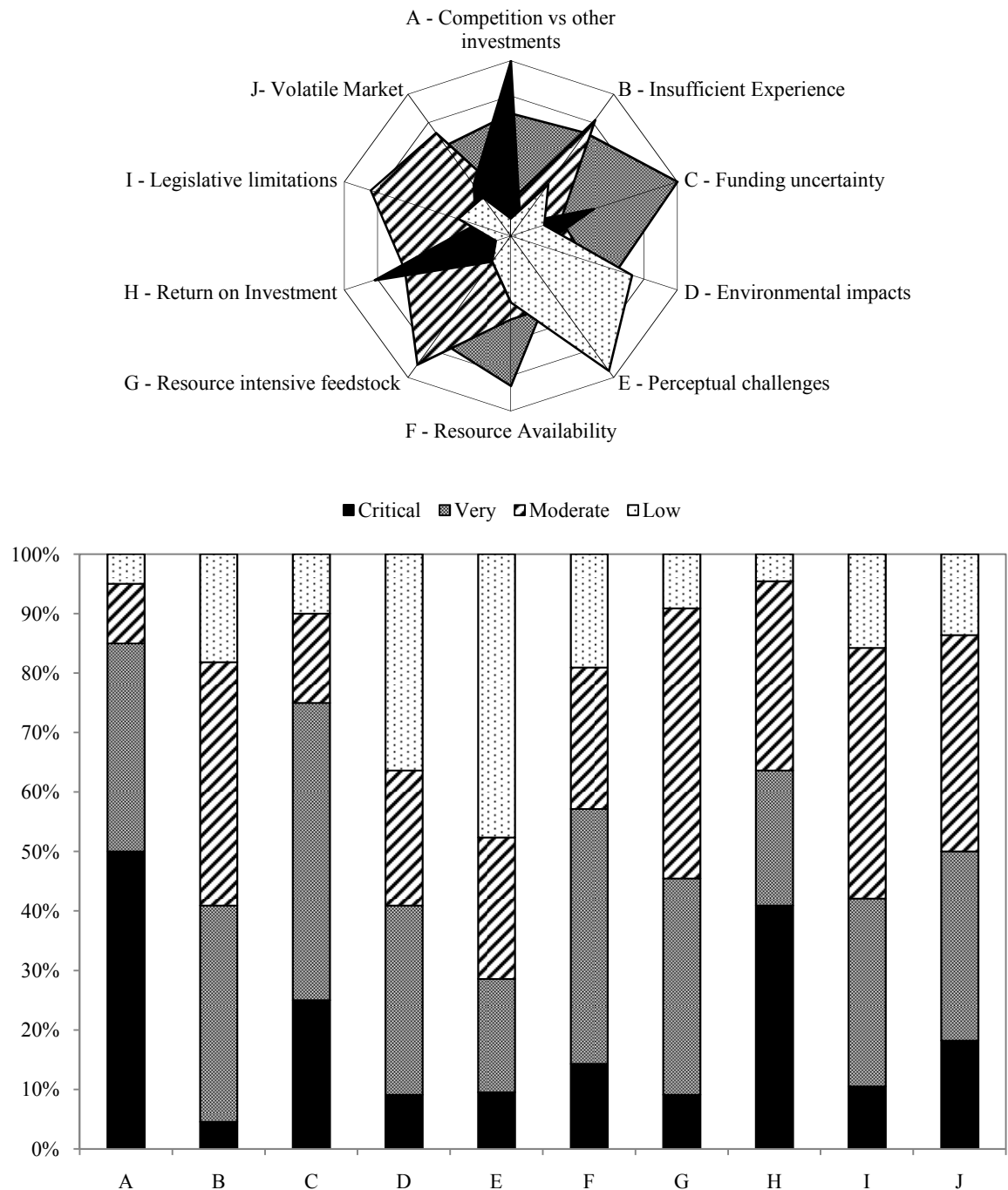


Figure 4-3 Barriers to bioenergy development according to farmers/suppliers of bioenergy feedstock

The predominantly significant (critically important) driver for the development of bioenergy according to farmers/supplier stakeholder was that bioenergy had to be profitable (76%) (Figure 4-3). If “very important” was also taken into account then this driver would contribute to 90%. The extent of this driver was high enough to mask other drivers. Other drivers included reducing the dependency on fossil fuels (75% between critical and moderate) and investing in a “growing market” was an important driver with 67% of the questionnaire share (between critical and moderate). The questionnaire also highlighted the least important driver as helping to meet Government targets (55% said this was least important) and adopting bioenergy for its potential environmental benefits (40% low importance).

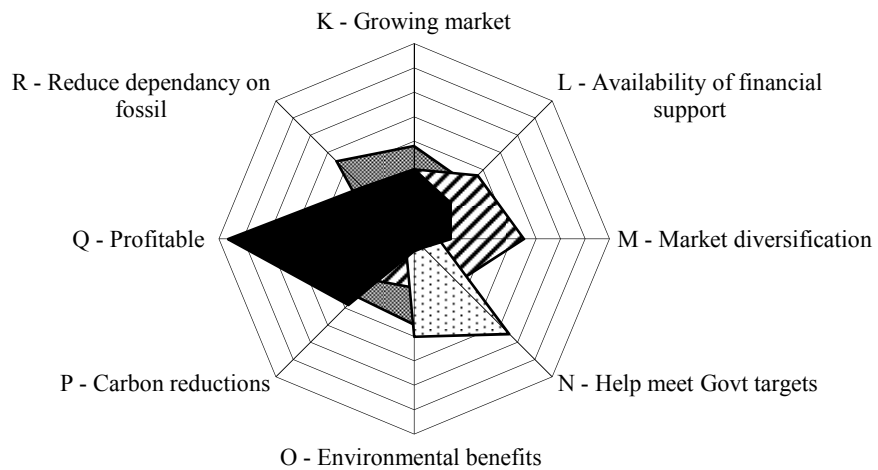


Figure 4-4 Drivers to bioenergy development according to farmers/suppliers of bioenergy feedstock

4.4.2 Developers/owner stakeholders of bioenergy projects

Barriers of critical significance to the development of bioenergy included technological barriers with conversion technologies/energy production and delivery (42% critical) (Figure 4-5). Legislative issues were also seen as a critical barrier (36%), whilst resource availability and development and operational costs were also of critical significance. Plant owners/developers saw perceptual challenges as a bigger barrier to bioenergy than farmers/suppliers did (50% very important). Finally, local planning issues and environmental implications of bioenergy were also seen as important barriers; 42% and 33% respectively (moderate/very important).

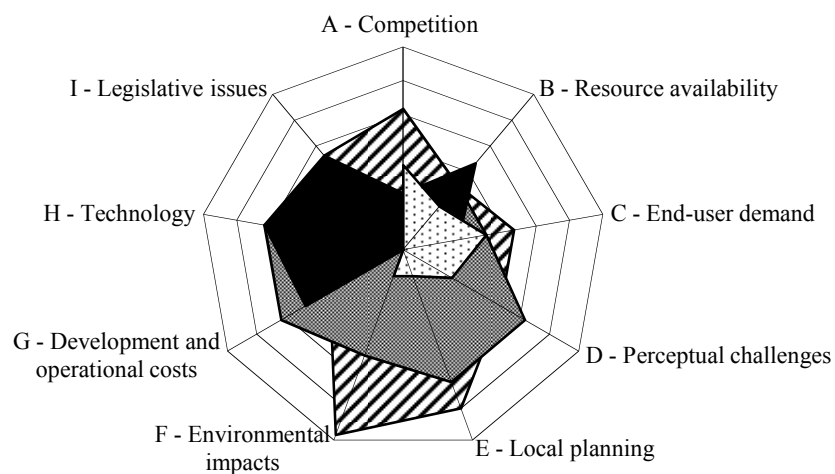


Figure 4-5 Barriers to bioenergy development according to developers/owners of bioenergy projects

The predominant drivers (Figure 4-6) for bioenergy according to the developers/owners included the benefits of financial reward/support (91% between critical and very important), preferring bioenergy over other renewable energy options due to its constant supply of energy (64% critical and very important) and entering a new market opportunity (82% mix of critical and very important). However, other benefits included a reduction on the dependency of fossil fuels (64% very important) and investing into a market with recent increased interest.

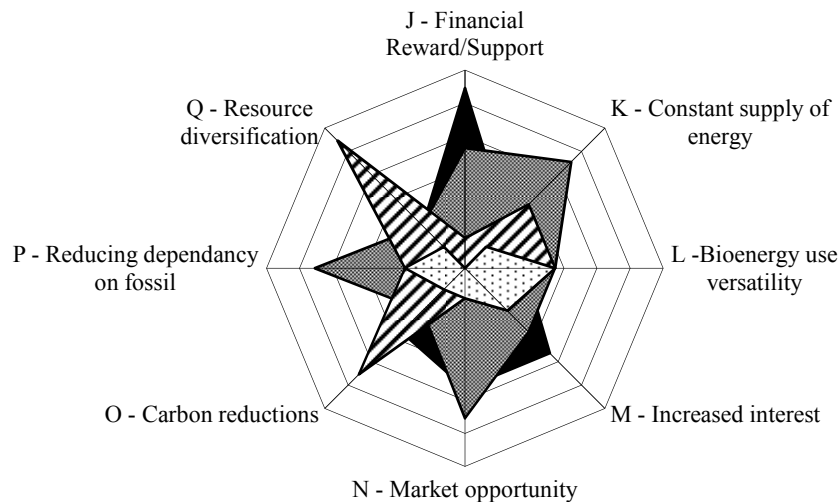


Figure 4-6 Drivers to bioenergy development according to developers/owners of bioenergy projects

The least significant drivers were less pronounced compared to the previous stakeholder group. The versatility of bioenergy use/feedstocks was seen as one of the least important drivers. This could be because owners/developers have fixed feedstock contracts set prior to starting a project. Other drivers of low or moderate importance included the reduction in carbon emissions and the potential of biomass resource diversification.

4.4.3 Primary end-users stakeholders of bioenergy

The primary barriers highlighted by this group of stakeholders included the elevated buying costs with respect to fossil fuels (88% between critical and very important) (Figure 4-7). Legislative issues, which included Government policy decisions/uncertainties of standards and funding mechanisms also contributed to a significant barrier (73% between critical and very important). The requirement for new infrastructure and insufficiency of energy availability were also important barriers (both were rated as critical or very important by 67% of the stakeholders).

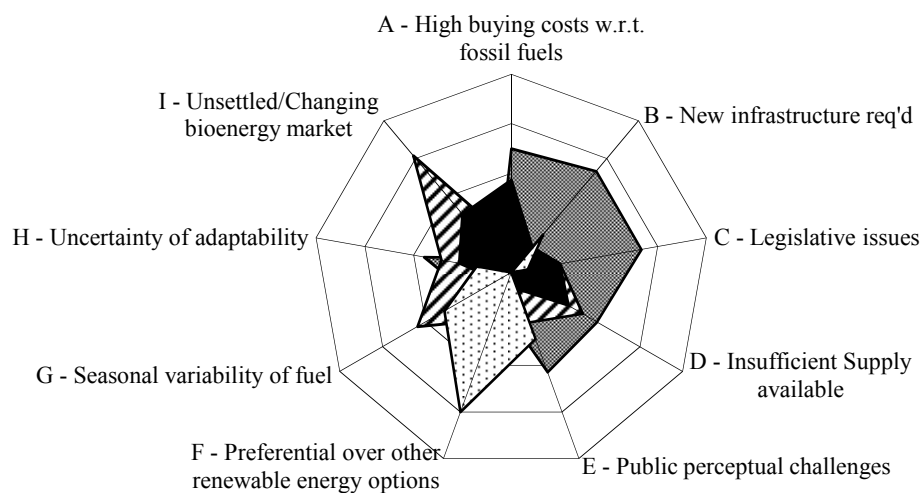


Figure 4-7 Barriers to bioenergy development according to primary end-users of bioenergy

Key drivers for this stakeholder group included reducing the dependency on fossil fuels (86% viewed as either critical or very important); shown in Figure 4-8. End-user stakeholders viewed bioenergy as beneficial in reducing carbon emissions. The least significant drivers included the versatility of fuel options and the opportunity to access a new market gap.

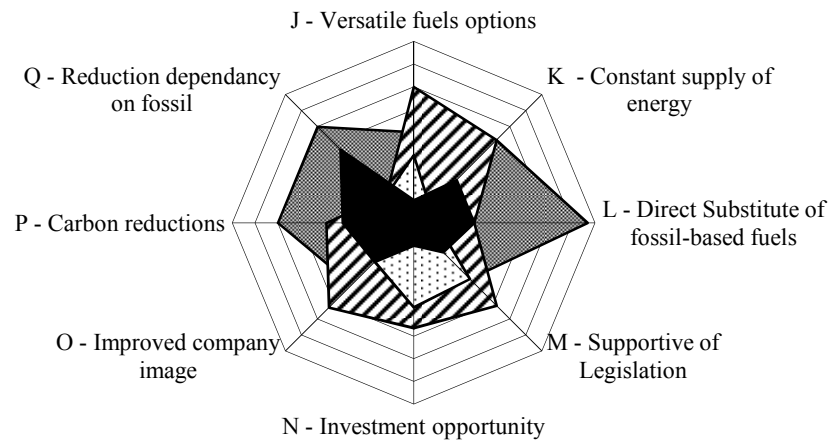


Figure 4-8 Drivers to bioenergy development according to primary end-users of bioenergy

4.4.4 Government/policy stakeholders of bioenergy development

The key barriers identified by these stakeholders included the availability of feedstock resources for bioenergy (63% between critical and very important) and the use of an unproven technology (56% between critical and moderate) (Figure 4-9). Other important barriers also included the threat that bioenergy could have on rising food prices and the uncertainties in identifying clear legislation and support for bioenergy. Although there were significant barriers identified, this group had the largest spread of results with no well-established patterns forming.

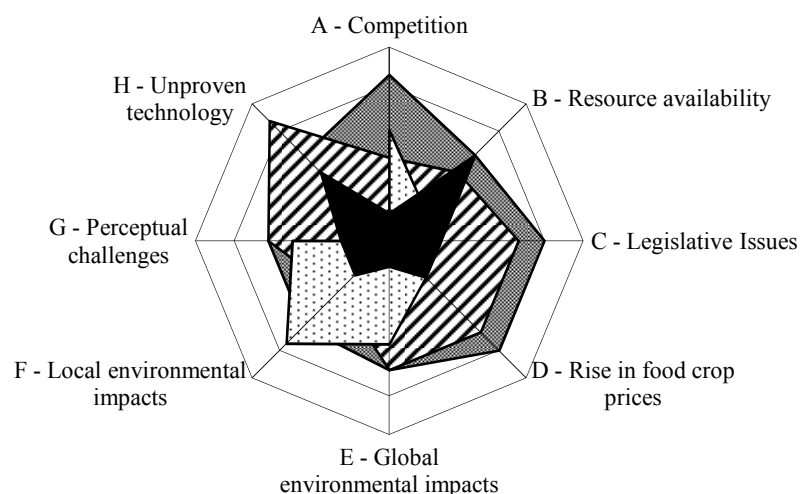


Figure 4-9 Barriers to bioenergy development according to Government/policy stakeholders

The most important drivers identified by this stakeholder group included the reduction of carbon emissions (81% between critical and important) and the reduced dependency on fossil fuel for fuel security (70% between critical and very important). The drivers within this group

were more pronounced and clearly visible, as can be seen by these two results (Figure 4-10). The least important driver was seen as the diversification of resources which could be of greater interest to owners/developers of bioenergy projects.

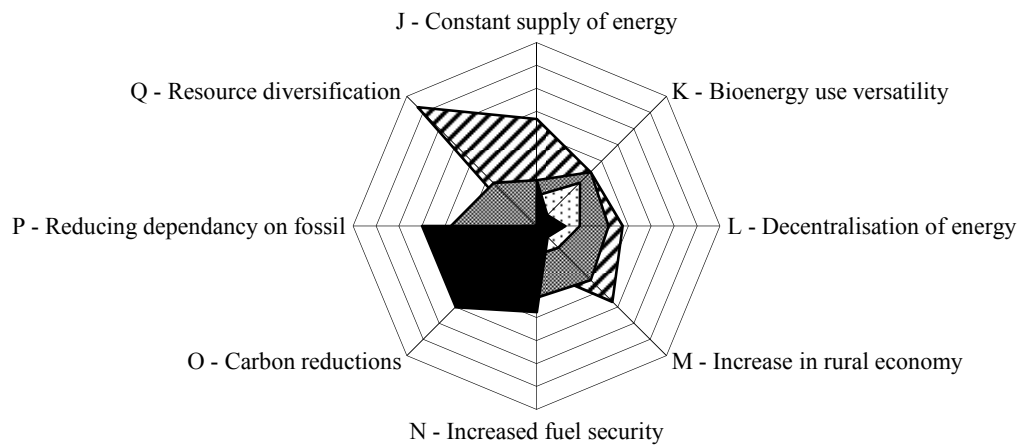


Figure 4-10 Drivers to bioenergy development according to Government/policy stakeholders

4.5 *Effects of following individual bioenergy pathways on barriers*

The results reinforced that the drivers and barriers to bioenergy would be affected by the bioenergy pathway chosen. Based on the obtained correlations, the survey results were contextualised for differing bioenergy pathways.

4.5.1 **Feedstock suppliers**

Based on the bioenergy pathway described by Hammond et al. (2008b), it is clear that feedstock supply for bioenergy can be grouped into two main categories; controlled production of bioenergy and uncontrolled bioenergy feedstock. Controlled production of bioenergy is feedstock which is planted and/or grown for cultivation, purposely for bioenergy use. The second type (uncontrolled) incorporates all types of waste. Waste is an uncontrolled source of feedstock because it is not produced solely for bioenergy. This can include municipal waste, animal waste and other farm by-products such as straw or processing residues.

The key barriers for controlled wastes related more towards the barriers identified within the stakeholder survey. For example physical resource, land use competition, return on investment and the use of a financially resource intensive feedstock. However, for uncontrolled bioenergy feedstocks these barriers may not be as significant. More critical concerns may be perceptual challenges, legislative issues and general financial barriers. These appeared to be common with AD processing operations (J.Prior, Summerleaze Ltd. 22/05/2007, personal communication).

Common barrier elements amongst all suppliers of bioenergy feedstocks were also present. These included economic considerations and security of financial reward. A high return on investment is essential for bioenergy to be attractive. However, minimising risks and ensuring secure Government support is also a common requirement.

4.5.2 Conversion plant developers/owners

Technology barriers were believed to have different effects depending on age and establishment of the conversion process. Anaerobic digestion for example is more widely used and economically viable than Biomass-to-liquid 2nd generation conversion processes. However both of these conversions are met with technological barriers. The study also recognized more “basic” conversion processes such as wood combustion or biogas direct combustion. These processes may not have technological barriers as primary reasons for failure of a project.

Common elements identified, regardless of the conversion technology, were the lack/uncertainty of resource availability. This is a common problem with all bioenergy projects and is widely considered the primary obstacle to overcome, prior to installing a bioenergy plant. A clear link was also present between critical economic barriers (development and operational costs, technology) and important economic drivers (financial reward, market opportunity etc). This highlights the strong interest in the economic benefits of bioenergy from a developer/owner perspective. This is similar to suppliers who displayed a strong drive originating from the economic benefits of bioenergy, but who also showed careful consideration of the financial threats which bioenergy could pose.

Overall, the barriers identified within this stakeholder group could be related to all bioenergy conversion processes. Other barrier similarities included competition with other energy sources, resource availability and legislative issues. However, the scale of the plant may affect other barriers such as local planning and perceptual challenges. For example, a domestic wood burner may not have the same visual impacts as a large-scale gasification plant.

4.5.3 Primary-end users

Primary-end users are the primary point of contact with the produced energy from biomass. It was found that this group also had a large variation in barrier rankings compared to the other stakeholder groups.

The main barriers considered applicable to transport fuel primary-end users were the high buying costs with respect to fossil fuels. Currently there are little or no financial savings for using biodiesel over fossil diesel (Biosulis 2009). Additionally biodiesel’s lower net calorific value equates to higher running costs in respect to fossil fuels. Other barriers which can impede on the performance of bioenergy for transport fuel is the compatibility of the fuel within existing systems and infrastructures. Although bioethanol and biodiesel are seen as direct replacements for fossil-based fuels there are a number of issues when operating these fuels within standard internal combustion engines, such as the corrosiveness of the fuel and the higher cetane number of the fuel leading to different combustion timing settings.

Electricity suppliers which are rewarded with ROCs after purchasing electricity (MWh) from bioenergy sources are faced with different barriers. The key barrier for this group may be the preference of other renewable options over bioenergy. For example if a MWh of wind energy is cheaper than a MWh of bioenergy, then the supplier would be more inclined to purchase the wind energy. The insufficiency of supply may also create a barrier due to the limited feedstock availability for conversion processes. A constant source of electricity is required and therefore season intermittency of feedstock supply may become a significant barrier.

Due to the lack of established renewable heat financial support, heat energy primary-end users are faced with very different barriers for the development and use of bioenergy. These include the legislative issues and an unsettled bioenergy market, which could be affected by Government policies. Additionally, the lack of increased financial reward could make bioenergy economically uncompetitive.

4.5.4 Government/policy

The barriers determined for this stakeholder group identified resource availability and unproven technology as fundamental barriers to overcome within the bioenergy industry. These were considered to be valid for all bioenergy pathways. Other important barriers which could affect all bioenergy pathways included the perceptual challenges of bioenergy, the competition against other energy sources and the effects on the local environmental.

It is evident that when considering bioenergy in the UK, the Government has addressed bioenergy as a whole, regardless of the specific bioenergy pathway (BERR 2007b). However, more recently there is evidence that bioenergy pathways are being addressed individually and policies are being created for specific bioenergy sources. This can be seen through the introduction of variable ROC values for different bioenergy options, with some bioenergy conversion processes being worth 2 ROCs per MWh whilst more conventional bioenergy conversion processes are worth less (BERR 2008c). A similar approach can also be seen through the FIT incentives (Ofgem 2010).

4.6 *Social impacts of bioenergy*

A key factor affecting the development of bioenergy is how it integrates within society. Although society was not considered to be a separate stakeholder, it could have a direct impact or an indirect impact on bioenergy development. This study examined the barriers from a bioenergy supply chain perspective. Integrating society or public perception within the bioenergy supply chain was not considered appropriate as this stakeholder group may or may not have a direct interest in bioenergy development.

Through the literature critique carried out for this study, public perception appeared to have a large influence on whether bioenergy projects succeeded or failed. Extensive studies such as (Upham & Shackley 2007; Upham et al. 2007; Upham & Shackley 2006; Upreti 2004; Upreti & van der Horst 2004) had previously highlighted the issues of bioenergy developments facing opposition from public organizations. Additionally, these studies showed that often public opposition was then transposed onto the Local Authorities, subsequently taking action against bioenergy projects. As a result this study could assume that Government/policy stakeholders should address the interests and values of the general public.

Overall conclusions from the literature showed that large-scale bioenergy projects were often met with hostility and scepticism from public groups situated near the proposed developments. This opposition was found to arise from uncertainties such as: understanding the impact on the local area; what the benefits to the local area are; how will it operate and are there similar past experiences which can be relied on (Upreti 2004). Often commercially 'green' technologies have difficulty answering such issues. The increased risk arising from these uncertainties can create a negative public perception.

The literature highlighted a number of examples where public opposition was the cause of failed bioenergy attempts. These failed attempts have been documented in section 4.2.1. These attempts were mostly situated in the South West region, presumably due to the availability of biomass resources. Two notable failed bioenergy attempts in the region were both wood gasification plants (Upreti 2004). These plants required a large intake of wood resources and therefore their location was suited in the South West of England. However, the South West region (in particular Devon and Wiltshire, where the plants were being proposed) is commonly considered an area of natural beauty and have a significant tourist presence.

Studies concluded that large biomass plants would encounter difficulty in gaining social acceptability from proximate communities (Upham & Shackley 2007). Large developments are often associated with visible and intrusive building constructions, increased transportation activity, increased pollution and risk of environmental damage, increased noise nuisance and potentially a detriment to the current economic value of the surrounding areas. Other concerns raised included the apparent mistrust between local communities and developers of biomass plants (Upreti 2004). This mistrust was caused by delaying or withholding information of the total development, which subsequently lead to negative opposition between the two parties.

A study conducted by Howes & Howlett (2000) and documented by Upreti (2004) highlighted that the UK public were generally unaware of bioenergy pathways. The study found that people often associated bioenergy to waste incineration or other unclean energy producing processes. More recently as general awareness and interest in bioenergy has increased, the potential benefits of first generation biofuels have been questioned. Biofuel production technology has rapidly become associated with doubtful environmental benefits (Sims et al. 2010). This was contributed towards by reports claiming that biofuels lead to possible deforestation and increased carbon emissions (RCEP 2004;The Royal Society 2008). These issues may have added more concern regarding the overall benefits of bioenergy across all bioenergy pathways.

From literature, it appears that bioenergy with respect to societal behaviour offers greater risks and concerns than benefits and opportunities. The apparent societal benefits could include: enhancing energy independency, achieving national energy targets, increasing rural employment and development and reducing the handling and potential cost of waste (IRGC 2007). However, based on previous experiences of bioenergy development, these opportunities could be outweighed by the risks affecting society and hence public perception.

4.7 Concluding remarks

The main barriers and drivers for bioenergy development were established according to different stakeholders along the bioenergy supply chain. The study highlighted the requirement for a strong link between the whole supply chain of bioenergy and the importance of influence from the Government. The study found that a number of similarities existed between the stakeholder groups. These common themes lay within the financial aspects of bioenergy projects. This was clear from both a drivers and barriers perspective. It was determined that the primary consideration for bioenergy schemes must be that they are

economically attractive, which then dictates the success of a project. Carbon reduction and reduction of fossil-fuel use was also a common driver amongst stakeholder groups. This signified the requirement to evaluate bioenergy systems on a net-energy basis, but also with environmental lifecycle assessment techniques. Three out of the four stakeholder groups identified resource and supply availability as an important barrier. This emphasizes the requirement for supply-chain development and co-ordination for all bioenergy pathways.

The implications of these results have been discussed in Chapter 10 and linked to the results of the resource assessment carried out in Chapter 3. The discussion addresses the link between the low uptake of regional bioenergy resource and the dominating barriers which are affecting each stage of the supply chain.

5 BIOGAS APPRAISAL TECHNIQUES – THEORIES & METHODS

The results from the regional resource assessment have highlighted the abundance of farm waste as a potential for bioenergy. This could highlight a significant uptake of biogas production from anaerobic digestion as a way of converting farm waste into useful energy. A detailed assessment of the sustainability of biogas production is therefore required in order to determine the impacts which this technology could have. The biogas production process will be assessed using a number of appraisal techniques which will address economic, environmental and thermodynamic capabilities.

The sustainability of an energy source is dependant on a number of factors. Firstly it needs to be energy positive (i.e. produces more energy over its lifetime than the invested energy): secondly, it needs beneficial or neutral impacts on the environment and finally it has to be economically viable. In addition to these requirements, it must also be sustainable in a social context. This thought process is closely linked to the interconnections created between engineering constraints, and economic and social spheres (adapted from Hammond (2004) following an adaption from Parkin (2000)). This is regarded as a holistic way to conceptualize sustainable development.

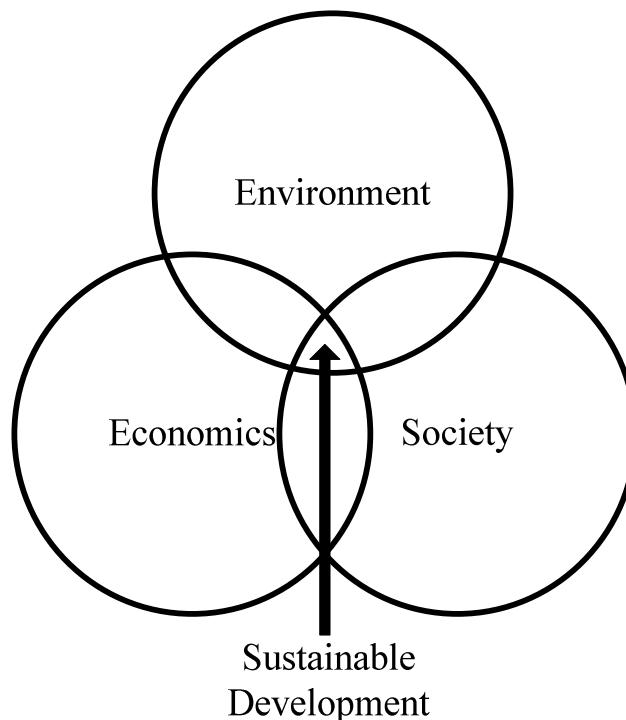


Figure 5-1 The three spheres of sustainability. Adapted from Hammond (2004)

There are over 200 definitions of sustainable development according to Parkin (2000). This particular form (shown in Figure 5-1) gives a clear and coherent representation of what sustainable development is and how it can be achieved. Developing a sustainable energy source involves three 'spheres' of influence: the environmental implications, the economic benefits/detriments and the impacts on society. Working on this theory, a methodology was developed by Hammond & Winnett (2007) to assess energy systems, by integrating

thermodynamic analysis, environmental life cycle assessment (LCA) and economic cost benefit analysis (CBA).

On a local scale, for example the South West of England, an alternative energy system must be thermodynamically sound and have positive or neutral effects on the environment. However, one of the key concerns of biogas or any bioenergy development is that it must be financially secure and offer a good return on investment (Adams et al. 2008). As a result, it is important to assess an energy system based on a financial investment appraisal technique.

The three areas of integrated appraisal in this case include energy analysis, environmental life cycle assessment and financial investment appraisal. This cannot be called a true integrated appraisal similar to that developed by Hammond & Winnett (2007) as it does not examine the economic value of the environmental impacts nor does it monetize the societal impacts. This study examined the actual financial appraisal of investing in a technology, which although has a narrower scope, is more relevant in addressing the concerns raised and discussed in Chapter 4. From this point forward, the alternative technique will be called a multi appraisal methodology/technique.

This chapter discusses the techniques adopted for carrying out a multi appraisal methodology of biogas for energy from an AD process. These techniques will then be implemented and findings will be represented individually in subsequent chapters.

5.1 The case studies used for the appraisal

The appraisal methodology was modelled against a number of existing operational AD plants (also referred to as case studies). In particular three AD plants were used for various analyses. These plants displayed adequate variation to cover most of the commonly used AD installations in Europe. The plants/case studies have been denoted as plant A, plant B and plant C. Additional data was also used where appropriate in order to compare literature theories, determine operational correlations and trends and to assess the impacts on AD process parameters. The additional data comprised of 61 AD plants currently operating in Germany. This data was kindly supplied by the Fachagentur Nachwachsende Rohstoffe e.V. (FNR) which is a government agency for renewable resources, founded by the German Ministry of Agriculture. The data was part of a project undertaken by Prof. Dr.-Ing. Weiland called "Scientific measurement programme for the evaluation of AD plants in the agricultural sector" (FNR 2005).

5.1.1 Case Study Plant A

Plant A was an operational AD plant situated in Scotland. The AD plant was considered small scale (250m³ digester size) and was fed purely on animal manure. As the most simplistic AD setup, it was a good representation of small-scale AD in the UK. The energy use from the plant was for thermal applications (hot water and central heating). The data for this plant was obtained from site visits, communications with the developer and data supplied through a number of reports. These reports have been referenced when mentioned.

5.1.2 Case Study Plant B

Plant B was also situated in the UK (Devon). The plant was amongst the largest installations in the UK (and Europe) with a total digester size of 8000m³. The plant was fed on a variety of feedstock, predominantly food processing wastes. Other feedstocks such as manure were also used. The plant was selected to represent large scale centralised AD. However, it also represented AD operating on food processing wastes as opposed to farm wastes. The energy from the plant was converted to electrical energy and fed into the national grid. The plant did not have a heat recovery system. The data for this plant was obtained from a site visit, communications with the developers and plant operator and finally through a number of reports. These reports have been referenced when mentioned.

5.1.3 Case Study Plant C

The final plant was also a large scale AD plant (plant C) situated in Germany. The key difference here was it relied solely on farm feedstocks including farm manure (generally over 90%) and some crops. The crops used were commonly silage crops such as maize or grass. The plant was indicative of large-scale AD, solely fed from farm feedstock. It also represented an example of combining electricity production and heat generation through the use of CHP. Both of these energy sources were being commercially sold. This plant was chosen as it showed a high gas yielding biogas plant using predominantly animal manure, therefore considered suitable for the South West of England. The data for this plant was obtained from FNR (2005) and referenced where appropriate.

5.1.4 Case studies used within the multi appraisal technique

The type and number of case studies used within each appraisal technique was chosen based on the data requirement, the output required and the time constraints. The energy analysis used all three case studies to obtain an overall energy performance indication of the plants. The financial investment appraisal focused on the best performing case study from the energy analysis and compared this against the small scale AD application. The LCA which required detailed operational and manufacturing data was applied to one case study (plant A). This was chosen as the feedstock was single source and hence the emissions could be calculated with the least amount of uncertainty. Additionally the results from the LCA could be readily interpreted for larger scale plants using single feedstocks. The choice of case study for each appraisal technique has been shown in Table 5-1.

	Energy Analysis	Financial Appraisal	Life Cycle Assessment
Plant A	x	x	x
Plant B	x		
Plant C	x	x	

Table 5-1 Choice of case study (Plant A, B or C) for each appraisal technique

5.2 Energy analysis

Energy analysis is defined as “determination of the energy sequestered in the process of making a good or service within the framework of an agreed set of conventions”, stated by the International Federation of Institutes of Advanced Studies (IFIAS) (Slesser 1978). The term to describe the total energy requirement of a product or service is called the Gross Energy Requirement (GER). This terminology also follows the definitions set out by IFIAS (1974).

In order to determine the energy requirements to produce a product or service, all the energy flows within a system must be examined (Hammond 2007). This technique is referred to as energy analysis and follows the basis of the First Law of Thermodynamics, the conservation of energy. Energy analysis encapsulates the whole lifecycle of a process or product and can determine the energy use and where appropriate, the net-energy output of a process.

Lifecycle energy analysis was developed during the 1970s and has been widely used since the first oil crisis during the initial period of the 1970 decade (Allen et al. 2008b). A common basis for energy analysis was created in 1974 at a workshop organized by the IFIAS (Mortimer 1991). Although these conventions were created over 30 years ago, they are still widely regarded as the common basis for current energy analysis and are used within renewable energy appraisal techniques (Allen et al. 2008b; Gagnon 2008; Herendeen & Brown 1987; Lewis 1977).

The concept of energy analysis can also be useful in determining the efficiency of an energy producing system and can compare different energy sources. However, there are difficulties with this as not all energy sources are equally effective (Slesser & Lewis 1979). An example Slesser & Lewis (1979) use is:

“Examine the production of 45MJ of heat energy from oil, hard coal and wood. 1 kg of oil will produce 45MJ of heat, whilst for the same amount of heat; one would require 3 kg of wood and 1.5 kg of coal. However, the effectiveness of the heat from oil burning is higher than that of the coal and wood, even though the energy released is the same. This is because it is at a higher temperature”.

This approach takes into account the energy source in terms of thermodynamic quality, i.e. the Second Law of Thermodynamics. This law states that although work input into a system can be fully converted to heat and internal energy, not all the heat input can be converted into useful work (Hammond 2007). As a result, maximum conversion efficiency exists between heat and work; called the Carnot Cycle (Slesser 1978). An example of this can be seen within the UK national electricity production system. The average electrical conversion efficiency for UK power generation is 33% (Allen et al. 2008b). The rest of the energy is dissipated through heat.

5.2.1 Methodology for energy analysis of biogas

To determine the total energy requirement of the biogas production process all the energy inputs were examined. These included direct inputs such as electrical work or heat and indirect inputs, which consisted of energy requirements to provide the direct inputs. When considering an energy production plant such as an AD unit, the energy allocated to the

construction material was also taken into account along with the direct and indirect energy inputs to generate and use the materials.

These energy requirements from point of conception to delivery of energy are known as the total energy required or alternatively known as the embodied energy. The extent to which this iterating process is carried out depends on the system boundaries of the analysis (Slesser 1978). System boundaries can vary depending on the time-scale, study motives, data availability and accuracy requirements of the study. It is therefore important that the system boundaries are stated within the study itself.

Within the analysis reported in Chapter 7, the system boundaries accounted for the extraction and production of the materials required for the AD plant construction. The energy required to operate the AD plant was considered, as was the energy required for producing, collecting and transporting the feedstock (required where appropriate). The energy output of the biogas was calculated along with its efficiency conversion into a utilisable energy form. The summation of the energy values at each regression was then calculated to be the GER.

To determine the total energy input of an energy system it was necessary to summate the operational energy inputs *and the internal energy of the fossil resource used*. The internal energy of the fossil resource used was included, because the GER is the total amount of energy resource sequestered when delivering that end-use energy to society. In order to examine the use of fossilised resources it was important to associate the resource with an energy value. This is often referred to as the calorific value of the fossil resource. The GER is recognized by the following equation (Slesser 1978):

$$GER = \text{Energy Resource in the Ground} + GER \text{ of other inputs (amortised where appropriate)} \quad \mathbf{5-1}$$

An accounting of fossil resources is required as the quantification of the GER should include all the energy flows traced back to their naturally occurring form in the ground. To calculate the *total* energy requirement of a system, the system boundary is taken around the Earth (Slesser 1978). Using accumulated resources diminishes the remaining available resource for future uses, as is the case with fossilised fuels. Therefore the stored energy within fossilised resources was included within the study as this energy would no longer be available.

Renewable resources are more complex and less straightforward when creating a system boundary around their energy flows. Fossil-derived energy forms are a ‘capital’ resource which depletes over a period of time. Renewable resources can be viewed as an energy ‘income’ of the planet (Hammond 2004), as they are renewed over a much shorter period of time compared to fossil or nuclear fuels. As a result, they are not a ‘capital’ resource. Using biomass for example, the internal energy within the biomass (obtained from solar) should not be included in the GER as this is a renewable ‘income’.

In some cases, the use of GER in energy analysis may not be appropriate. For example if one were to compare the conversion efficiency of a solar PV cell against an equivalent power rated electricity diesel generator, the use of GER would show a disproportionate disadvantage (in terms of conversion efficiency) towards the diesel generator. In this case, the IFIAS identified other energy totals: process energy requirement (PER) and net energy requirement (NER). The

NER technique is more suited when analysing the process efficiency of energy production techniques, rather than assessing the resource savings incurred (Mortimer 1991). It is a useful tool to assess and track inefficiencies within a process as it does not include resource consumption. Although these terminologies have been addressed, they were not required for this study.

The Energy Requirement for Energy (ERE) is used to describe the energy requirements expressed per unit of energy at point of delivery (Slessor 1978). The ERE is therefore the sum of all primary energy dissipated to yield one unit of delivered energy (Slessor 1988). The ERE should always be greater than one for fossil fuels as energy is required to produce and deliver energy. As delivered energy becomes harder to source from fossil fuels, the ERE will subsequently increase. Typical ERE values of fossil based energy systems have been displayed in Table 6-1 (Allen et al. 2008b; Mortimer 1991). The ERE can be expressed by the following equation:

$$ERE = \frac{GER}{\text{Delivered Energy}} \quad 5-2$$

Energy use	Energy source	ERE MJ _{resource} /MJ _{delivered}	
		(Mortimer 1991)	(Allen et al. 2008b)
Heat	Coal	1.071	-
	Natural Gas	1.141	-
	Oil	1.131	-
Electricity	Coal	3.21	3.52
	Natural Gas	3.52	2.32
	Oil	3.81	4.62
Transport	Oil	1.131	-
	<i>Diesel</i>	1.108	(Elsayed & Mortimer 2001)
	<i>Petrol</i>	1.18	(Dale 2007)

Table 5-2 Energy requirement for energy (ERE) for different delivered energy

The figures in Table 5-2 show that the energy requirement is greater than the delivered energy due to accounting for the ‘capital’ sequestration of the particular resource. This highlights the consumption of fossil resources as a ‘capital’ resource, which cannot be regenerated. Therefore if a comparison were to be made between fossil-fuel energy source and renewable energy sources using the ERE, it would not represent the energy efficiency of the process, rather the savings (or indeed increased use) of fossil-fuel energy. This study adopted the use of ERE to represent the energy requirements for delivering biogas to different energy uses, such as direct heat, electricity and as transport fuel. The results also reflect how this type of data can vary significantly between studies. These changes are due to the assumptions made within each study and the selection of the system boundary.

When comparing biomass fuels against fossil-based fuels, literature shows that energy analysis can be tailored and manipulated to vary outcomes, either showing them as an energy

sink (Pimentel & Patzek 2005) or an energy source (Dale 2007). This is because analysts do not specify whether the GER or NER is used. Secondly, conventional energy analysis does not include energy inputs from labour, whilst some studies include this (Pimentel & Patzek 2005). It is apparent that energy analyses do not always follow the guidelines originally set by the IFIAS. The aim of this study was to examine the production and use of biogas as energy, adhering as best to a standardised energy analysis methodology (IFIAS 1974).

5.2.2 The system boundary of energy analysis

The system boundary for energy analyses has been shown in Figure 5-2 and this approach was adopted for the study. The analysis included the embodied energy of plant construction, the inputs entering the plant and the outputs from the process.

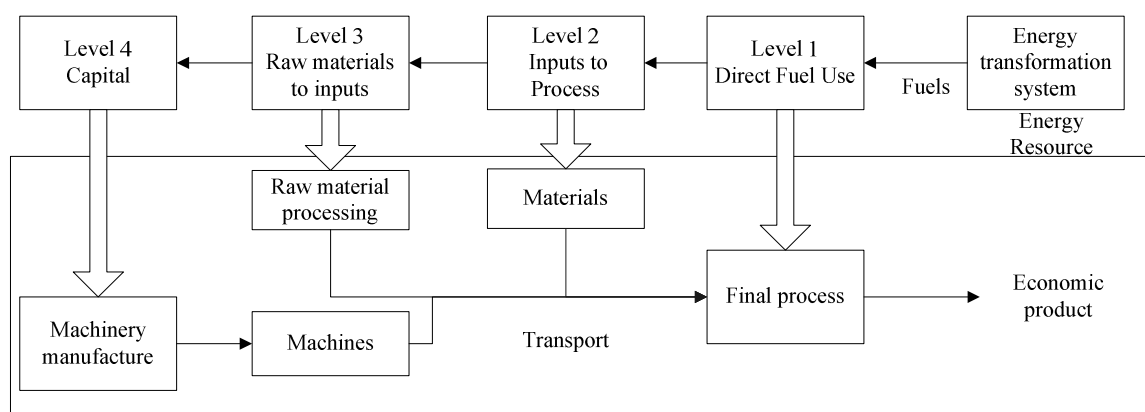


Figure 5-2 The system boundaries of energy analysis (Slesser 1979)

Direct energy inputs to an AD process can generally be divided into two areas. These are on-site energy use and off-site energy use. Off-site energy consumption includes the production and collection of the feedstock, the transport and the post-digesting handling energy use of the feedstock. Feedstock production energy is more applicable to crops, which are specifically grown for biogas purposes. On-site energy consumption is more critical and in the case of biogas production, should always be considered within the boundaries of study. The energy use on-site includes pumping, mixing and heating requirements for the feedstock. The on-site energy can be categorized into two further groups: heat energy and electrical energy.

For this study, the use of the digestate as a source of natural fertiliser was considered as a displacement for the production and use of artificial fertilisers. The study therefore also analysed the impact on energy analysis with and without fertiliser as an AD output. However, expanding the system boundary further included processes at the wider extremities of the study (Hospido et al. 2009), which led to an increased uncertainty. Consequently, the energy analysis results were shown with and without the displacement of fertiliser.

5.2.3 Closing statement on energy analysis

In order to examine the net energy analysis of an energy system it is essential to adopt a standardised approach. Therefore, the system boundary of the study was clearly defined as this was a key determining factor affecting the results. The aim of the study was to determine the following:

- Understand the common energy inputs and outputs of the AD process, highlighting the effect of process parameters;
- Determine the gross energy requirement (GER) of large scale and small-scale biogas production units; using a series of case studies;
- The energy requirement for energy (ERE) for delivered end-use energy for various biogas production plants. This was used to determine the process efficiency of biogas production;
- Determine the effect on energy output from using different feedstocks.

5.3 *Environmental life cycle assessment (LCA) of biogas*

The second step of the multi appraisal technique detailed in this section highlights the background and methodology adopted to determine the environmental impacts of biogas production from an operating AD plant. The theory of LCA methodology was investigated and assessed, along with its application on biogas production from “cradle to grave”. The assessment was carried out by using data obtained from visiting an AD plant and collecting operating, manufacturing and emission data. This data was then used to carry out an LCA using the technique described in the following sections.

5.3.1 **Introduction and overview of LCA**

To evaluate the environmental impacts of a product or process, its entire lifecycle must be examined. The life cycle assessment (LCA) evaluates environmental impacts, from raw material extraction to the final stages of end-of-life of a product or process. The resource extraction and consumption is accounted for, along with air, soil and water discharges at each stage. These extractions and emissions are then assessed to examine the environmental impacts of the whole life cycle. LCA differs from an energy analysis as it considers a wider range of environmental impacts associated with a process. Energy analysis is often used as a process optimisation tool (Berglund & Borjesson 2006), whilst LCA is a holistic consideration of where the environmental burdens lie within a process (McManus 2001; Spielman et al. 2007b).

The first LCA studies originated from the mid to late 1960s. However, the founding of the Society for Environmental Toxicology and Chemistry (SETAC) in 1979 resulted in a significant development in LCA methodology. LCA then became more coherent and standardised (Sonnemann et al. 2003). The first standardisation applied to this methodology was not until 1993, where the first ISO standards were published to develop international norms and rules for LCA (Sonnemann et al. 2003). These created a benchmark for all future LCAs. In 2006 an update of these standards resulted in the formation of two standards, ISO 14040:2006 Environmental management - Life cycle assessment – Principles and framework and ISO 14044:2006 Environmental management — Life cycle assessment — Requirements and guidelines (BSI 2006). According to these standards, the LCA process consists of the following stages:

Goal and scope definition – Clearly defining and describing the process or product. This is where the practitioner explains the reasoning of the study and identifies the system boundaries.

Life cycle inventory (LCI) compilation and analysis – Quantitative data is collected on energy, water and materials usage, along with environmental releases for a particular process (Curran 2006). This process is iterative and is addressed throughout the entire LCA process. Quantities are gathered using S.I base units.

Life cycle impact assessment (LCIA) – This stage gathers the data from the inventory (LCI) and examines the effects of the inventory on human health, ecosystems and natural resources. Mandatory elements of this stage include the classification (assigning LCI results to selected impact categories) and characterization step (calculating the category indicator results). Optional elements include normalising the data (converting it to dimensionless form by applying it to base values) and weighting or valuation (converting the indicator results of different impact categories to one value or point score). This stage of the LCA is achieved by adopting a specific methodology for modelling the environmental impacts associated with LCI results.

Interpretation – This stage identifies issues or significant findings from the results. The evaluation also examines the completeness, consistency and sensitivity analysis of the results. From this, a conclusion can be drawn highlighting the limitations and recommendations from the findings.

Although the LCA can be grouped into these four stages, the process requires the analyst to return to previous sections in order to update and verify the data. Therefore, all four sections are linked during an LCA. This has been highlighted in Figure 5-3.

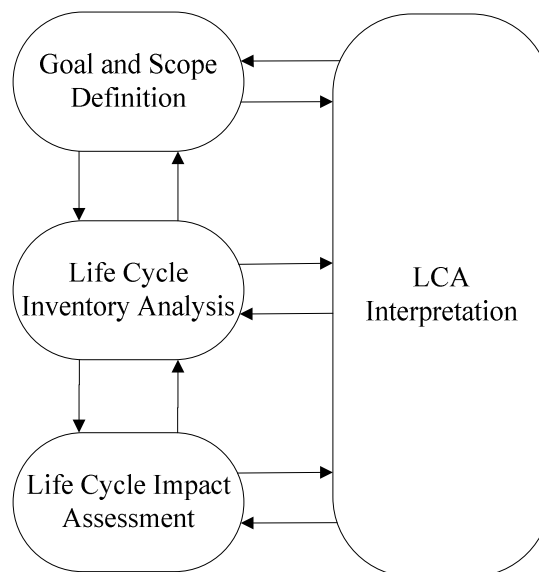


Figure 5-3 The LCA framework – Source (BSI 2006;Curran 2006)

LCA can identify areas within the process, where environmental burdens could be alleviated. These uses of LCA are considered (by the author) to be on a micro-scale. The benefits of LCA on a macro-scale highlight for policy decision-makers the need to address environmental concerns. In the more recent applications of LCA, these techniques have been aimed to be clear and simple to understand and interpret for non-scientific audiences.

Other benefits of LCA include the use of it for promotional marketing purposes. The results of LCA in the most simplistic form are relatively easy to understand regardless of the audience's background. For example, if product B creates more ozone depleting gases than product A, then the customer would opt for product A over B.

5.3.2 Limitations of LCA

Although there are benefits in the use of LCA, the collection of data required to generate reliable results can be inaccurate and extremely time consuming. One of the most common problems found amongst LCA practitioners was obtaining suitable and qualitative data (Bras-Klapwijk 1998; McManus 2001; Reap et al. 2008). Often the practitioners of LCA have to weigh the availability of data against time required to obtain and subsequently carry out the study (Curran 2006). There are a number of other limitations associated with the use of this methodology. This section is not intended to address all practitioner issues, as extensive studies have already been undertaken and published (*ibid*). However there are particular limitations to this study, which must be acknowledged prior to using such a tool.

LCA is a holistic approach to assessing environmental burdens. Therefore adopting a broad scope within an analysis ultimately affects the quality of the analysis as areas of the study must be simplified (Guinée 2002). One of the most common issues raised regarding the use of LCA is its inability to address localised impacts. This methodology is suited to global environmental impacts such as climate change and ozone layer depletion. However, increased toxicity levels and acidification over a small area will have a larger impact than the same quantities over a larger area. LCA cannot differentiate between different geographical areas or locations.

LCA is also a time independent analysis tool and in some cases, time aspects are considered critical for environmental tools (Hofstetter 1998). In theory, the correct use of a complete LCA should only be applied after a process or a product is accomplished. LCA therefore should not be used to model or predict the environmental impacts prior to a process or product being complete (Hofstetter 1998). The reason for this is that LCA is not capable of modelling the effects of the environmental impacts in future scenarios, as this would require modelling for a future society and societal values (*ibid*). Additionally, the data quality and accuracy required for LCA studies signifies that only existing processes/products can be assessed using this technique. However, LCA has been used during design stages in order to minimise environmental impacts from material selection.

A final issue relating to LCA regards the optional stages within the LCIA stage, which involve converting quantitative results into subjective evaluative results. This is achieved by applying a weighting value to different environmental impact categories. This evaluates the significance or the weight of the environmental impacts against each other. However converting quantifiable results into valuation results required value judgement and can be subjective.

Adopting LCA as an assessment tool for this study was based on a number of motives. Firstly, LCA considers process stages in a similar method to energy analysis where direct and indirect processes are examined. The assessment was undertaken on an existing AD process; therefore the use of LCA was more suitable. Secondly, LCA is a standardised approach with international standards associated with the methodology. Therefore LCIA has effectively been

validated as a modelling tool for environmental impacts. It is also considered a critical tool for undertaking integrated appraisals of technologies. The results of LCA could also be used to undertake cost-benefit analysis (CBA) in order to address the costs associated with the environmental impacts.

5.3.3 Available databases for the lifecycle inventory stage

A simplistic method for describing lifecycle inventory databases is to use a common household product such as a chair. The lifecycle inventory (LCI) would include all the emissions and resource requirements from the materials, manufacturing processes and assembly processes required in the whole life cycle of the chair manufacture. During these processes, the use of electricity may be required at various stages. This must also be accounted for, as this is part of the chair's lifecycle. The production of electricity is commonly known as a standard process. This process can be used for a number of different LCAs and does not have to be made specifically for an individual LCA.

There are a number of extensive databases available, which incorporate LCI data for standard processes. Information used to create these databases is derived from specialist consultancies, extensive literature research and a compilation of measured and calculated data. There are a number of available databases for example IDEMAT (Industrial Design Engineering of Delft University of Technology). This database however, is based mainly on Dutch datum sources. Other databases include the ETH-ESU 96 representing data for Swiss and European processes, which comprises of around 1,200 processes.

One of the most comprehensive databases available is the EcoInvent database. This contains over 4,000 processes. The database has been developed by the Swiss Centre for Lifecycle Inventories. It is currently the largest and most detailed database available to LCA practitioners and is constantly updated by the Swiss Centre for Lifecycle Inventories (Frischknecht & Rebitzer 2005).

Throughout this study, standard process data was obtained from the EcoInvent database, whilst specific data was obtained through plant visits and extensive literature reviews of similar AD processes. The EcoInvent database was the only database used in this study, due to the clarity and transparency of the data collection and calculation. Information regarding the EcoInvent database has been published in a series of 25 reports (Swiss Centre for Life Cycle Inventories 2007).

5.3.4 Methodologies for assessing life cycle impact assessments (LCIA)

When assessing the environmental impacts associated with the AD plant within the study, the life cycle inventory (LCI) data represents the environmental loads. The LCI however, does not examine the environmental damage of the AD process. LCIA is a method of evaluating the implication of potential environmental impacts through computation of the LCI results. This process enables an interpretation of how the process behaves based on its environmental performance.

The LCIA process is carried out by applying the LCI data to impact categories and category indicators. An example to represent this has been reproduced from Sonnemann et al. (2003);

“when considering the environmental impact ‘global warming potential’, it is understood that substances such as carbon dioxide, methane, nitrogen oxides and hydrocarbons, all contribute towards this environmental impact. To understand the capacity of the pollutants to generate greenhouse effect they can be measured by the potential to generate CO₂ equivalents. Therefore, the global warming potential can then be multiplied by a corresponding factor to obtain a global value of CO₂ equivalence. As a result the environment impact category has been measured based on the LCI data.”

Similar to the overall LCA procedure, the LCIA stage incorporates compulsory steps which must be taken, governed by the ISO standards (BSI 2006). These steps were carried out within this study as part of assessing the LCI data. The procedure steps are as follows:

- **Impact category selection** – The impact categories to be evaluated are chosen;
- **Classification stage** - Assignment of environmental loads for each impact category, aggregating the data into the separate categories;
- **Characterisation stage** – This stage calculates the category indicator results. This is done by quantifying the contribution each impact category (greenhouse gases, ozone gases etc.) makes to environmental damages (global warming potential, acid rain etc.);
- **Normalisation stage** – An optional stage where the characterised results are divided by a selected reference value for each impact category, making the values dimensionless. Ranking and grouping of the impact categories can now take place;
- **Weighting (Optional – not encouraged by ISO Standards)** – Based on value choices which have been pre-determined, the normalised values are then compared based on the severity of the impact. This stage is optional and not encouraged by the ISO Standards, due to the subjective nature of the output results (BSI 2006).

The characterisation process within LCIA requires the use of established and accredited methodologies (Curran 1996; Reap et al. 2008). Examples of these include Eco-Indicator 99, CML 2001 and EDIP97, amongst others. Selecting the impact model to use within an LCIA depends on the original goal and scope of the study. However, these models also have varying levels of data quality, accuracy and validity of computational procedures.

Previous studies have shown that different results can be obtained for the same impact categories depending on which methodology is chosen (Dreyer et al. 2003; Hauschild et al. 2008). Therefore a careful understanding of how the LCIA methodologies were created must be understood.

LCIA methodologies can be classified into two categories. These are: midpoint-based (problem orientated) impact assessment methods or damage orientated (end-point) single score methods (Jolliet et al. 2003; Jolliet et al. 2004; Mizsey et al. 2009). Midpoint and endpoint refer to the level within the assessment at which the methodology terminates the analysis (the point at which the respective effects are characterised (Sonnemann et al. 2003)). Midpoint indicators measure a substance effect or strength and do not consider the damage or severity of the impact (Sonnemann et al. 2003). For example, when emissions such as CFC and halons are analysed within an LCA, a midpoint characterization process would represent the results in terms of ozone depletion potential based on the chemical’s reactivity or lifetime in the atmosphere. Endpoint characterisation takes the analysis one step further and accounts for the

effects of the depletion in ozone layer, for example skin cancer, crop damage, marine-life damage etc (Bare & Norris 2003).

Endpoint methodology analyses the expected consequences (damage level) from the impact potentials. Modelling up to this stage increases the risk of uncertainty within the calculation procedure, because understanding the damage of an impact category can be subjective. Nevertheless, the benefit of this technique is that the results can be represented more clearly and effectively. Modelling the effects of an environmental impact is more meaningful to a wider audience (and decision-makers) than stating a simplistic, basic emission figures or equivalences.

5.3.5 The LCIA methodology adopted in this study

Two of the most established and respected LCIA methodologies are called Eco-Indicator 95 and Eco-Indicator 99 (EI95 and EI99). The normalisation techniques for these LCIA methodologies are based on average European figures (based on 15 EU member states rather than the current 27 member states). The methodologies are acknowledged as being the standard investigation tool for LCA and are practiced in over 100 countries according to Mizsey et al. (2009). However, the use of EI95 has been superseded by the use of EI99.

EI95 results are outputted using SI based unit equivalence. For example, all greenhouse gases are grouped and scaled towards an equivalent CO₂ in kg; hence kg/CO₂eqv. From an engineering perspective, this methodology represents clear and tangible results in SI units. However, the methodology is now out of date and can no longer be used for an LCA study. EI99 is one of the most current methodologies. It considers the endpoints of the impact categories, hence the actual effects created on society by (for example) the release of greenhouse gases etc. Therefore, EI99 models the impacts further and simulates the effects of the impacts.

In this study, the Eco-Indicator 99 tool was adopted. The methodology focuses on three environmental damages (endpoints) which are human health, ecosystem quality and resource depletion. A comparison between this methodology (end-point) and EI95 (mid-point) has been shown in Figure 5-4.

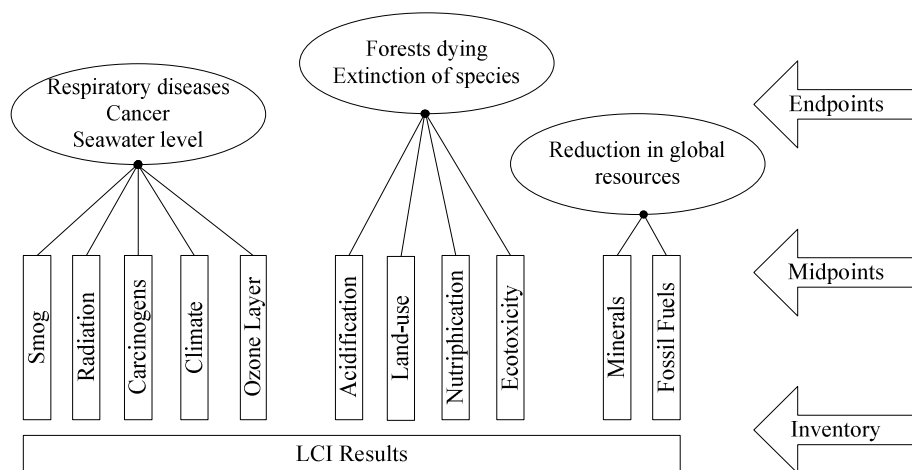


Figure 5-4 Link between LCIA midpoint and endpoint approach – Source (Goedkoop et al. 2008)

Ultimately, the focus of the study was to determine the potential damage which biogas could pose on the environment; this is why an end-point methodology such as EI99 was chosen. Although there were other end-point LCIA methodologies available, the study focused on using EI99. This was because as the study was based in Europe, it was appropriate to focus on a methodology specific for this geographical area.

5.3.6 How EI99 characterises and normalises the LCI data

An understanding of how EI99 characterises and normalises the data has been explained within this section, as this forms the basis of the results from the LCA study. As the methodology was used within this study, it is important to understand how the methodology was created. This section is therefore a summary of the methodology conception and is based on the main EI99 methodology report (Swiss Centre for Life Cycle Inventories 2007).

The creation of EI99 methodology was created firstly by analysing the weighting stage within the impact assessment process. The step was performed by a panel of 365 LCA experts and the importance of each of the three main endpoints was weighted. These were:

- Damage to human health;
- Damage to ecosystem quality;
- Damage to resources.

These were considered to cover most if not all possible environmental concerns, attributed to a process or a product. The damage categories were ranked and weighted in terms of importance (this stage is subjective). The result from the panel showed that human health and ecosystem quality both had a 40% weighting, whilst resource depletion was weighted with the remaining 20%.

The panel was then asked a series of questions regarding attitudes and perspectives on society. Based on these results the respondents were grouped into three different archetypes. The three groups were established to deal with the uncertainty of the results. The three perspectives were as follows: Hierarchist, Individualist and Egalitarian. These three archetypes were selected from the Cultural Theory Framework (Hofstetter 1998;Thompson et al. 1990), commonly used within social science to establish cultural attitudes. From these results, three versions of Eco-Indicator 99 were created based on the perspective choices.

Following the agreement of different archetypes and the weighting of damage categories, the damage models were subsequently created. These models (or the series of processes and calculations) are used to convert the LCI data into a characterised data form, which can show the effect of each inventory towards the damage category. The three damage models are as follows:

- Damage to human health was modelled using Disability Adjusted Life Years (DALY);
- Damage to ecosystem quality was modelled using an expression to show the percentage of species that have disappeared in a given area over a specified time due to the environmental load. The unit of this was $\text{PDF} \cdot \text{m}^2 \cdot \text{yr}$;
- Damage to resources was modelled using a measure of surplus energy required for the future mining of resources. This was measured in MJ.

DALY (Disability Adjusted Light Year) – DALY is defined as the consideration of losing one whole year of healthy life and is a measure between current health status and an ideal health situation (WHO 2010). The model has been developed for five different impact categories which fit under the umbrella of human health damage. These include: respiratory and carcinogenic effects, climate change, effects of ozone layer depletion and the effects of radiation. The use of DALY to quantify these damages was developed by the World Bank and the World Health Organisation and is regarded as a common approach for measuring damages to human health (Hofstetter 1998). The damage model works in four steps, these are:

1. Fate analysis - This links the emissions (in basic S.I. units) from the LCI to a change in concentration in emission over a specified volume.
2. The change in concentration is then converted to a dose. This is called the exposure analysis.
3. Once the dose is known, the effects on human health can then be determined, for example the number and type of cancer (Goedkoop & Spriensma 2001). This is called the effect analysis.
4. The health effects from the previous section are then linked to DALY. This is done by multiplying the disability rating of the health effect by the number of years of life lost or affected. The disability rating is a score given between zero and one. A score of one is certain death, whilst a score of zero is not serious.

Ecosystem Quality ($PDF \cdot m^2 \cdot yr$) – This model gives the results as the percentage of the disappeared fraction of a species (PDF) per unit area (m^2) over a specific time period (yr). This model has been developed for damage occurring to ecosystems such as ecotoxicity, acidification, eutrophication and land-use. The model for each impact category is calculated slightly differently.

- **Ecotoxicity** – This model also incorporates similar procedures as the DALY model, including fate, effect and damage analysis. The potentially affected fraction (PAF) of a species is measured in relation to a type of toxin and its concentration. This is measured against the population of species when no toxic stress is applied. However, the technique does not show observable damage and hence cannot be easily convert into PDF. Therefore, a conversion factor is used to link these results to PDF. Further literature of this can be found by reading Goedkoop & Spriensma (2001).
- **Acidification/Eutrophication** – These are considered as one impact category in the model. The model also consists of a fate analysis and a damage analysis. The damage to seed-bearing plants is modelled under normal conditions. The probability that a plant species can still thrive once the emission is released is then measured. This is called probability of occurrence (POO). PDF is equal to $1 - POO$. The model has only been used to simulate the Netherlands and therefore is representing the whole of Europe, based on a single country alone. Although this is a rather crude method, it is one of the only available methods to model these effects.
- **Land-use modelling** – This is based on the European Land Use Model (Corine 1991; Corine 1992). In basic terms, the model simulates that the more natural the land use is, the higher the species richness and accumulation. Subsequently, the more industrial or urbanized the land use is, the lower these values become and hence the higher the $PDF \cdot m^2 \cdot yr$ is. It is based on empirical data of plant species occurrence on different land-use types and areas.

Resources (MJ) – This models future energy requirement to extract resources and has been based on work from Muller-Wenk (1998). The extraction of minerals and fossil fuels was considered for this model. The unit is a MJ of surplus energy. For mineral data, various established models are used to relate the availability of the resource to its concentration (Chapman 1983; Goedkoop & Spriensma 2001). Using a correlation between the greater the extraction of the mineral resource and the lower the quality of the resource, this theory simulates the effect of depleting minerals (Chapman 1983). Therefore a higher energy would be required to extract the same quality of minerals.

The methodology is also used to model the energy requirements for fossil fuel extraction. This models the future use of oil shale and tar sands. Based on a depleting discovery rate and an increased extraction rate the model predicts the required energy to extract future fossil fuels. Data on the depleting discovery rate is obtained from a number of sources discussed by Goedkoop & Spriensma (2001). The model accounts for a number of fossil and mineral resources, a detailed list can be found in Appendix C. The model did not account for phosphorus depletion.

There are a total of eleven damage categories, consisting of: respiratory and carcinogenic effects, effects from ozone layer depletion and radiation, climate change, ecotoxicity (or toxic stress), acidification and eutrophication, land-use and resource depletion of minerals and fossil fuels. The methodology clearly states that the models were created based on emissions and land-uses in Europe. Therefore all damages occur in Europe, except for damages to resources and damages created by climate change, ozone layer depletion, carcinogenic emissions, air pollutants and radiation (*ibid*). A list of the complete characterisation data for EI99 has been shown in the Appendix C.

5.3.7 Allocation of environmental impacts

In order to determine the environmental implications of the AD process the emissions from the process were allocated to the output, known as allocation. In order to carry out an allocation process for AD, the functions (outputs) of the process were examined. The allocation procedure occurs prior to the actual LCA and therefore has been described within the methodology section. The data for this calculation steps was based on the case study Plant A, for which the LCA was carried out on. The allocation results are then used throughout the LCA (Chapter 8).

It was apparent that a typical biowaste anaerobic digester could have three output functions. These are:

- Disposing of a waste, therefore avoiding waste entering other streams such as landfill;
- Producing a biogas for energy purposes;
- Producing a natural source of fertiliser with uniform fertilisation properties.

This is a multi-output process (Spielman et al. 2007b) and requires the emissions of the process to be allocated to the three outputs. Although the present study was similar to that of Spielman et al. (2007b), it was concluded that only two outputs would be considered as opposed to the three mentioned. The two outputs considered were:

- Producing a biogas for energy purposes;
- Producing a natural fertiliser thus reducing the use of artificial fertilisers.

The waste used for the anaerobic digestion process at the farm was entirely cow manure. As a result, it was not considered a waste product, therefore it did not require waste disposal. This meant that the LCA in this study assumed that the AD process had only two outputs.

The next stage was to determine the percentage of emissions to be allocated to each output. This was carried out using two methods: mass and economic allocation. These are amongst the most common methods of allocation, along with energy allocation. Both techniques hold different benefits and drawbacks. Economic allocation, which uses a market value, can be used to reflect the energy use within a lifecycle. However using this approach only covers one aspect of the system (Curran 2006). In addition to this, an economic allocation is subject to variable changes in market values within the system. For example if a system output were to displace kerosene domestic heating oil, then the variation in market value between July 2008 (65p/litre) and January 2009 (37p/litre) would be nearly double (BoilerJuice 2009). For the purpose of this study, both allocation methods were examined to determine the difference between the two.

5.3.8 Economic (market value) allocation

Using a detailed calculation procedure (shown in Appendix B) the economic value of biogas for heating and the equivalent fertiliser value was calculated. The allocation results show that fertiliser value equates to £8.79/m³ of waste and a biogas value is £1.23/m³_{waste} (Table 5-3). Therefore, based on economic allocation the environmental impacts associated with the AD plant should be allocated 88% towards producing and managing the natural fertiliser and 12% towards making biogas for domestic energy consumption. This is based on market values of artificial fertilisers and available quantities from dairy manures (Nix 2009).

Economic Allocation			
	Biogas for Heating	Biogas for fertiliser	Total
Cost/m ³ of Waste (£)	1.23	8.79	10.02
Allocation ratio	12%	88%	100%

Table 5-3 Economic value of biogas

5.3.9 Mass (or volume) allocation

A detailed calculation methodology for these results has been presented in Appendix B. From a total annual input of 653m³ of waste, the valuable fertiliser was calculated to be 5,895 kg based on assumptions and prices from Nix (2009). The other useful output from the system was the biogas used for space heating, hot water and cooking. However, it was not possible to determine the exact daily biogas consumption for these requirements as the Rayburn and boiler were operated upon requirement. Therefore, average national figures for domestic hot water, space heating and cooking energy consumption were obtained using the BREDEM-8 model for domestic energy demand. These figures have been shown in Table 5-4.

	Space Heating	Water	Cooking
Farmhouse energy demand (MJ/day)	142.74	36.32	21.63
Methane equivalent per day (m ³ /day)	3.99	1.02	0.61
Biogas equivalent (m ³ /day)	6.88	1.76	1.05
Total biogas demand	9 m ³ /day		

Table 5-4 Breakdown of biogas used for domestic energy

By converting the biogas to weight (assuming a density of 1.225 kg/m³), the biogas output could be compared to the fertiliser output. The allocation results have been shown in Table 5-5.

Mass Allocation	Biogas for Heating	Biogas for fertiliser	Total
Weight dist. Of AD operation (kg)	3,961	5,895	9,856
Allocation (%)	40	60	100

Table 5-5 Allocation of biogas based on mass

5.3.10 Correlation between mass and economic allocation

The results from both allocation techniques suggested that the majority of the environmental impacts should be allocated to the fertiliser production. These results were used when assessing the environmental impacts of using the biogas and fertiliser. Both allocations (economic and mass) have been shown within the LCA study in order to highlight the differential results.

5.3.11 Closing statement on life cycle assessment

The aim of the LCA study was to determine the environmental impacts associated with biogas production. LCA is a technique which enables the examination of a process or product's impact towards the environment. Similarly to energy analysis, the system boundary of an LCA is an important part which must be clarified prior to commencing a study. The issues and limitations regarding the use of LCA were also addressed. The issues such as system boundaries, uncertainty of inventory data and subjectivity of impact assessment methodologies cannot be eliminated. However, these uncertainties can be minimised through transparency during the study. The use of LCA methodology has subsequently been documented in Chapter 8.

5.4 Financial appraisal techniques

The study in Chapter 4 found that the growth and development of bioenergy was closely dependant on the financial viability of a project (Adams et al. 2008). Financial considerations are crucial and often overarching in the deployment potential of bioenergy. For this reason, it was necessary to examine bioenergy based on its financial viability.

Studying the economics of renewable energy systems is another method, similar to energy analysis and LCA, to assess the performance of the energy production system. A technique commonly used at the University of Bath to assess performance of various energy systems, is the 'integrated appraisal' study as described at the beginning of this chapter. These studies

have been carried out successfully on a number of energy generation techniques which incorporate energy analysis, environmental life-cycle assessment and environmental cost-benefit analysis (Allen et al. 2008a). These studies are intended to address a holistic approach to assessment of sustainable energy and are carried out by a team of engineers, scientists and economists.

The use of cost benefit analysis (CBA) enables the assessment of a project in terms of its economic viability. In order to measure 'Externalities' such as a reduction in GHG emissions or other pollutant emissions, the use of economic appraisal techniques can be used to measure their effect. The method values and monetizes all costs and benefits linked to the externalities. This technique is representative of the issues faced by society, thus representing the values of energy use to a wider scale of society (Allen et al. 2008a). However, considering environmental economics to assess sustainability of an energy system can generalise and obscure the impacts of different courses of action (Hammond & Winnett 2007). Environmental economics are not able to determine the actual environmental impact of a process or product. Therefore, it is critical to use economic analysis in conjunction with other sustainability assessment techniques in order to obtain a more holistic assessment.

Although CBA has the ability to assess environmental externality benefits, the monetary realism of whether an energy producing system can be implementable is dependant on individual financial appraisal. This technique will clearly indicate whether an energy producing system will be financially feasible over the whole life cycle. A financial investment appraisal can be used to estimate the net-present value (NPV), the benefit cost ratio (BC) and the financial payback time (years).

The analysis carried out in this study aimed to assess the potential financial viability of a bioenergy pathway through the adoption of financial investment appraisal (FIA). The use of FIA is well established and has been used to examine the financial payback of micro-generators (Butcher et al. 2006). This technique can be used to examine the future potential savings of a particular bioenergy process by discounting back from the initial investment (Slessor & Lewis 1979). This appraisal methodology was considered more appropriate for the specific regional case of the South West of England. Understanding and applying the methodology of CBA requires a range of skills and expertise, which were outside the remit of this study.

5.4.1 Life cycle costing

Similarly, to LCA and energy analysis, the financial assessment of an energy system is examined over the system's life cycle. From the author's experience within industry, LCA and life cycle costing (LCC) are commonly carried out alongside each other. LCA seeks to minimise the total environmental impact, whilst LCC seeks to minimise the total cost (Finch 1994). Recent LCA and LCC studies on Brazilian bioethanol production successfully highlighted that greenhouse gas emissions and ozone layer depletion were significantly reduced when compared to gasoline, whilst in terms of cost; bioethanol in Brazil was more economical than gasoline (Luo et al. 2008). This combination of techniques highlights how the benefits or drawbacks can be highlighted using two different approaches.

An important factor when undertaking LCC is to take into account the ‘time value of money’, which is based on the principle that a unit of money today is worth more than the same unit in the future (Finch 1994). This is because the money value of today could be invested and increased in the future. This technique is called discounting cash flow rate or internal rate of return (IRR), which will be explained in the following section.

5.4.2 Investment appraisal techniques

In order to quantify and assess the potential of a project, the typical investment is compared with the financial return inflows over the project’s lifespan. The most simplistic way to carry out this technique is to divide the initial investment costs by the annual operating savings. This result calculates the number of years for a project to payback. This is called the simple payback period (SPP).

If one were to take into account the ‘time value of money’ they would use an alternative technique. This technique is called present value (PV), which is the future savings discounted back from the present (initial investment) date. The difference between the PV and the capital investment is the Net Present Value (NPV) (Slessor & Lewis 1979).

In order to determine the PV, the monetary value is related to time through the discount rate. If one wanted to determine the PV of an investment today they would adopt the discounting approach, whilst to determine the future value of an investment, the compounding approach would be used.

Following the methodology from Twidell & Weir (2006), an investment of present value V_0 , can be compared to a future value of $V_i = V_0(1+r)$ after 1 year, where r is the discount rate. Applying this to n years and assuming a constant discount rate, results in:

$$V_n = V_0(1+r)^n \quad 5-3$$

By rearranging the above equation, it can then be applied to each transaction for each year n as shown:

$$V_o = \frac{V_n}{(1+r)^n} \quad 5-4$$

where the discount factor (DF) is given by:

$$\frac{1}{(1+r)^n} \quad 5-5$$

When considering an investment into a renewable energy source, such as bioenergy, it is generally considered hopeful to receive a saving (an effective income) by displacing other energy sources. This is called an annual return, or annuity R . Therefore, the present value V_p of the investment over a period of years N is the sum of all the annual present value V_o and is calculated by:

$$V_p = R \left[\frac{1 - (1 + r)^{-N}}{r} \right]$$

5-6

If an initial capital investment I was outlaid, the net present value NV_p can be simply calculated by: $NV_p = -I + V_p$. These calculations assumed a stable, competitive market and therefore r would be equal to the market interest rates.

These two techniques (discounted cash flow and payback period) are two approaches to determine the financial feasibility of an investment. However, the discounted cash flow (DCF) using the net present value has been more widely used within established literature (Slesser & Lewis 1979; Twidell & Weir 2006).

5.4.3 Choosing an appropriate discount rate

A discount rate was chosen in order to simulate future cash flows to be estimated and discounted to their present value (Twidell & Weir 2006). The discount rate chosen for this analysis was based upon the expected return from investing capital rather than investing elsewhere (this is known as the opportunity cost of capital). The required rate of return of an investment is on the long term cost of borrowing in the market place (Finch 1994). Discount rates are often different depending on whether it is public or private investment.

If a project has a high level of uncertainty and is funded by the private sector, a high discount rate is often chosen, as the invested money is desired to be recuperated as quickly as possible. However, if a secure investment is made, or if public sector were to invest, a lower discount rate would be chosen. The current test discount rate (TDR) employed by the UK Government for investment appraisals is 3.5% (Allen et al. 2008a). Some studies of renewable energy projects have carried out an investment appraisal with a 0% discount rate (Butcher et al. 2006). Due to the relatively high levels of uncertainty of biogas production, a 5% discount rate was chosen for this study.

5.4.4 Other conventions and benchmarks used within financial appraisal techniques

There are a number of other benchmarks used to display the financial performance of an investment. Some of these have been used within the study in Chapter 9, whilst others have been discussed for completeness.

Simple Rate of Return (SRR) – This is expressed as a percentage per year of return. It is the inverse of the simple payback period. The value highlights the percentage of the return per year. This is a very simplistic approach to financial investment appraisals, which has not been carried out within the study.

Benefit Cost Ratio – This is an indicator highlighting the ratio between benefits of the investment relative to its cost. These benefits are expressed in discounted present values. In nontechnical terms this ratio will show how many pounds are expected in return, for every pound invested into a project. This indicator can verify quickly whether a project will generate or sink money. If the value is greater than 1, the investment will generate money. If the ratio is lower than 1, the investment will lose money.

5.4.5 Closing statement on financial investment appraisal techniques

The need to address the financial aspects of bioenergy has been highlighted as a key requirement for the successful deployment of bioenergy in the UK (Adams et al. 2008). The direct costs and benefits faced by investors therefore needed to be examined. In line with the energy analysis and LCA, this procedure was conducted on biogas production and use. The key aspects of the analysis included:

- Examining the life cycle costs of biogas production and use;
- Examining the life cycle financial benefits of biogas production and use;
- Assessing the optimum route (financially) for biogas use (transport, domestic gas or electricity production);
- With the information gathered and assessed, concluding whether biogas production is commercially viable for the region, whilst highlighting the potential impacts of biogas production deployment.

This study formed the final stage of the multi appraisal of AD biogas production for the South West of England. The aspiration of the study was to determine how implementable the AD bioenergy pathway would be for the South West of England. Using this multi appraisal methodology, this allowed for a holistic examination of the potential for biogas production in the region.

5.5 *Summary of adopting a multi appraisal technique*

The adoption of a multi appraisal technique was used within the thesis in order to assess the sustainability of biogas production for the South West of England. The study of these three chosen appraisal techniques highlighted the extent of detailed examination necessary to determine whether a bioenergy pathway is a viable solution for the region. In Chapter 2 it was emphasized that there are a large number of bioenergy pathways which are affected by feedstock type, conversion process technology and end-use of energy. Each of these pathways should be analysed using a multi appraisal technique such as the one described within this chapter.

Through this series of techniques, the suitability of a particular bioenergy pathway for the South West of England was made. The assessment of biogas production from AD was chosen as a suitable pathway for the South West of England, based on its abundance of feedstock resources and its relatively low demand on existing agricultural production systems. The multi appraisal technique was intended to complement the results from the resource assessment as these alone could not be used as a sole benchmark for determining an optimum bioenergy pathway.

6 THE POTENTIAL OF BIOGAS FROM ANAEROBIC DIGESTION

A methodology suitable for assessing biogas production from anaerobic digestion has been described in Chapter 5. The methodology requires an in-depth appreciation and understanding of the technology. The work reported in this chapter analyzes the process of anaerobic digestion (AD) in further detail. The work also highlights how varying AD process parameters can influence the performance of biogas production.

The chapter examines the performance of a range of AD plants across Europe to determine the links between performance and operating parameters. The core data enabling this assessment was kindly supplied by the Fachagentur Nachwachsende Rohstoffe e.V. (FNR) which is a government agency for renewable resources, founded by the German Ministry of Agriculture. The data was part of a project undertaken by Prof. Dr.-Ing. Weiland called "Scientific measurement programme for the evaluation of AD plants in the agricultural sector" (FNR 2005).

6.1 *Biogas as a bioenergy*

Biogas is one of the most versatile biomass-based fuels for energy conversion, as it can be used for a number of energy-related applications. The methane portion (generally 50-75%) can be combusted either directly to produce heat or via a reciprocating engine or a gas turbine. Methane, which has a net calorific value (NCV) of 35.8MJ/m³ at 15.5°C and 1.01 bar (Harasimowicz et al. 2007), is also the prime component of natural gas, which is used for domestic heating, cooking and electricity generation.

The overall energy potential of biogas is determined by its quality. This is the amount of methane in relation to carbon dioxide. The higher the methane concentration, the higher the gas quality, as there is a larger combustible percentage of gas. The main uses for biogas will be discussed in more depth in the following sections.

6.1.1 **Biogas for heat and electricity**

Electricity from biogas can be generated via internal combustion engines (ICE), by combusting the methane as a fuel. ICE can operate with a biogas quality as low as 45% methane. Other power generators include compression ignition engine (CIE), Stirling engines, fuel cells, or gas turbines (Deublein & Steinhauser 2008). The low conversion efficiency of this type of biogas utilisation (around 30-40% for an ICE) means that combining electrical generation with heat supply is an attractive alternative to recuperating the lost heat from the combustion process. This process is called combined heat and power (CHP). CHP enables the heat produced for electricity generation to be used for heating requirements such as space heating for example. This form of energy use increases the efficiency of conversion to up to 85-90% (Deublein & Steinhauser 2008).

6.1.2 **Biogas for transport**

The use of biogas as a transport fuel is not uncommon, and in various countries this setup is well-established. For example in Sweden, biogas has been used as a vehicle fuel for nearly two

decades. In 2006, the country had over 6000 vehicles registered to run on biogas (Jonsson et al. 2007). Biogas is mainly used as a road transport fuel, as opposed to air or train transportation. Other occurrences from Sweden show that biogas is used on public buses, distribution vehicles and taxis (Borjesson & Berglund 2006). Biogas for transport use requires the gas to be cleaned to remove hydrogen sulphide, water and other particulates. It is also recommended that the remaining CO₂ is also removed, as this significantly improves the calorific content of the fuel. These two processes are termed as “gas cleaning and upgrading”. The biogas can then be injected and used as vehicle fuel (Jonsson et al. 2007). These processes are energy intensive and therefore reduce the net-energy output of adopting biogas for vehicle fuel.

There are two methods of storing the biogas/methane within a vehicle; these are in compressed form or liquefied (National Society for Clean Air 2006). Compressed biogas is usually compressed to a pressure of around 200bar and is recognized to have significant CO₂ reductions for transport use when its whole life cycle is considered (Concawe 2007). Meanwhile, liquefied biogas uses a cryogenic transformation process in order to reduce the temperature of the gas in the region of -160°C, thus producing a liquid gas (Johansson 2008). This technology can also be used to separate the CO₂ within the biogas through condensation; due to the condensation point of CO₂ being higher than that of CH₄ (*ibid*).

6.1.3 Biogas injected into a natural gas network

Biogas is commonly used for cooking in rural areas of developing countries (Limmeechokchai & Chawana 2007). In rural India, it is estimated that energy for cooking accounts for over 80% of the total energy consumption (Purohit et al. 2002), therefore the use of biogas for cooking could have significant environmental and developmental benefits. In the UK, biogas could be injected into the national gas grid (NGG). The process for this energy source is very similar to that of compressed biogas for transport.

Interest in the injection of biogas into the national network has gained momentum over the past year. A report commissioned by the National Grid claimed that by adopting suitable government policies, biogas could offer up to 50% of the UK's gas demand by 2020 (National Grid 2009). However this could only be delivered with an associated cost of around £30 billion, equating to around £100/MWh, due to the large costs associated with the production of biogas.

6.2 *The carbon balance of biogas*

Although methane (CH₄) can be combusted for energy generation, if allowed to enter the atmosphere in its un-combusted form, it becomes a powerful greenhouse gas. Compared to carbon dioxide (CO₂), methane has been estimated to have a global warming potential up to 23 times greater for equal volumes of gas (Themelis & Ulloa 2007; IPCC 2006). Biogas production and use for energy can be considered as a carbon neutral or a low carbon technology as the carbon dioxide released from the combustion process is subsequently retrieved through the photosynthesis of the feedstock.

One of the most common feedstocks for biogas production is animal manure. It is estimated that around 88 million tonnes of manure is produced annually in the UK (Mistry &

Misselbrook 2005). This corresponds to just under 900 kt of methane per year; assuming a gas density of 0.68 kgm^{-3} , approximately 1,300 million m^3 of methane (DEFRA 2008e). In 2007, methane accounted for 8% of the UK's greenhouse gas emissions, based on global warming potential. Of this, 38% of methane was contributed by agriculture. By adopting AD within the UK agricultural sector, methane emissions that are currently dispersed into the atmosphere could be used to generate energy and also reduce the greenhouse contribution from the agriculture sector. However, it is often difficult or impossible to accurately quantify the methane savings from biogas production.

6.3 *Design of AD systems*

There are a number of potential AD design setups, but overall the process is similar for all (Deublein & Steinhauser 2008; Ward et al. 2008). These include batch reactors, continuous flow reactors with single or multiple reactor stages and storage process (also known as plug-flow digesters). Single stage digester types have a single tank where all four stages of the biological breakdown for methane production is carried out. Multi-stage reactors have two or more digester tanks and can divide the biological breakdown into separate stages. This improves the stability of the process, especially with volatile materials such as fats etc.

The most common type of digester in Europe is the storage flow-through process in which feedstock is fed into the reactor continuously, whilst the digestate is discharged in stages (Deublein & Steinhauser 2008). AD designs can vary depending on input material, quantity, seasonal ambient temperatures and financial investment availability. The design should ideally allow for maximised biogas yield, high organic loading rate and operate over the shortest retention time possible (Ward et al. 2008).

Some of the factors affecting the design of an AD plant include the composition and organic content of the intake material, the regularity of available feedstock and the operating temperature. Other non-performance factors include the land availability for the plant, the climate in which the plant will be operating and the potential use of the digestate at the termination of the digestion process.

A simplified AD process has been shown in Figure 6-1. The feedstock is collected and passed onto a digestion tank (digester) where the feedstock is mixed, either by stirring or pumping recirculation. The feedstock is maintained at a predetermined temperature in order to maximise the efficiency of the methane yield. This process then initiates the methane release from the feedstock. The process is undertaken for a number of days, generally between 10-100 days depending on the operating parameters of the AD plant.

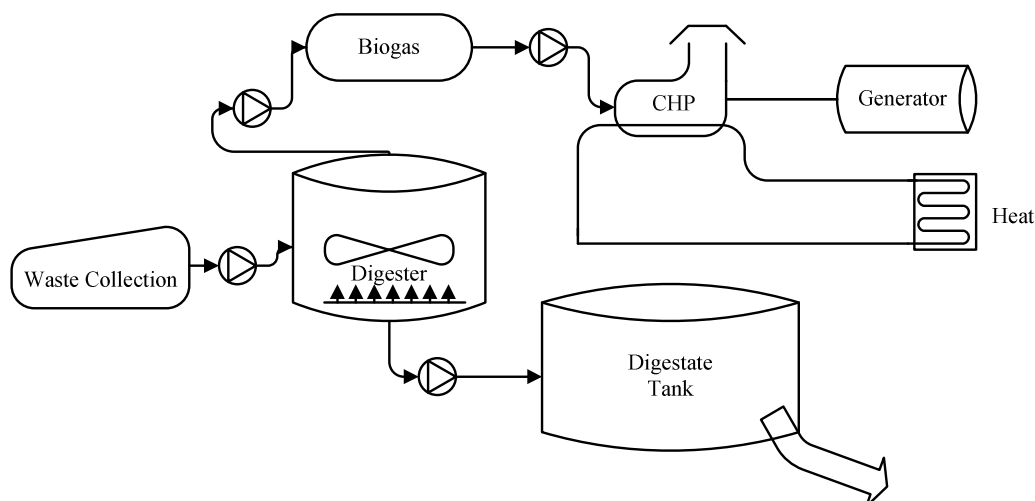


Figure 6-1 Simplified process layout of an AD plant

When the methane from the feedstock has been maximised, the waste (digestate) is pumped to a separate tank and then used either as a natural fertiliser or sent to landfill as general waste. The methane produced is subsequently stored in a separate tank or bellows and then processed or cleaned ready to be combusted. The heat can be partially inputted back into the system to warm the digester, whilst the electricity (if this is produced) can be used to power the mixer and pumps. Excess heat and electrical energy can be transmitted outside of the plant for external uses.

6.4 Anaerobic digestion performance parameters

The production of biogas from AD comprises of bacteria decaying the organic matter in the absence of oxygen. The process undergoes four key phases of biological breakdown. These include hydrolysis, acidogenesis, acetogenesis and finally methanogenesis, shown in Figure 6-2. The first stage hydrolysis is where primary compounds such as fats, carbohydrates and proteins are broken down into sugars, fatty acids and amino acids. The acidogenesis stage converts the latter into carbonic acids, alcohols, hydrogen, carbon dioxide and ammonia. The final two stages convert acetic acids, carbon dioxide and hydrogen into methane and carbon dioxide (Deublein & Steinhauser 2008). These processes can be undertaken simultaneously or separately.

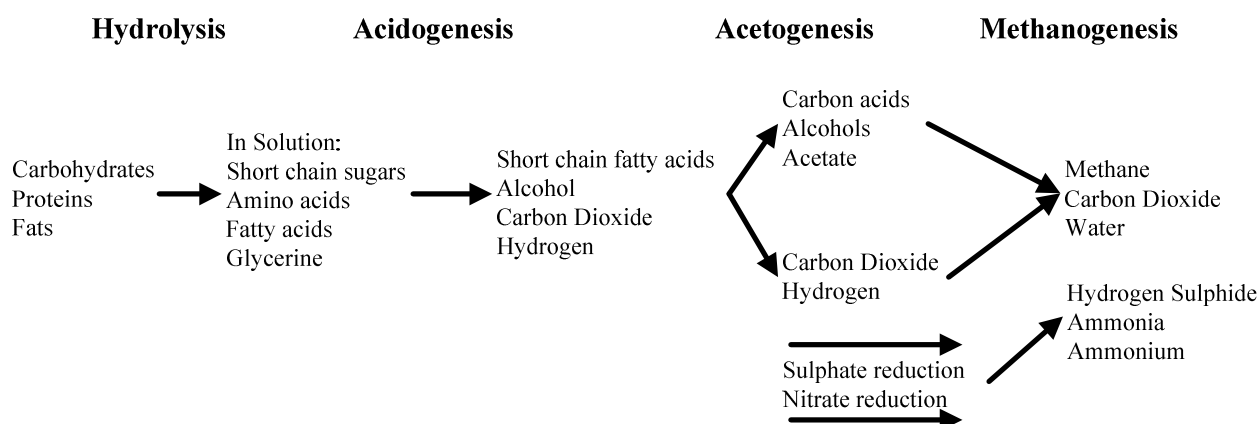


Figure 6-2 Biochemistry of methane gas production. Adapted from Ecofys (2005)

The performance of AD can be affected by a number of parameters. Research into the kinetics of methane production has led to a greater understanding of what these parameters are. A

useful model to describe the behaviour and performance of methane production from fermentation was formed by Contois (1959) and successfully used by Chen & Hashimoto (1978). This was subsequently used by Chen (1983) to analyse the performance of methane production from pig manure. The main process parameters have been shown below, highlighting the effects of each factor.

6.4.1 Total solids and volatile solids concentration

The total solids (TS) are defined as the residue remaining after a wastewater sample has been evaporated and dried at a specified temperature (103 to 105°C) (Tchobanoglous et al. 2003). The TS concentration is directly proportional to the viscosity and density of manure (El-Mashad et al. 2005). As the TS increases within a material, its ability to generate biogas is also increased.

Higher TS concentrations also increase the difficulty in pumping and mixing the material. Materials with a high TS content can be used as a co-substrate (an additional feedstock) to the AD plant in order to increase the biogas yield when mixed with materials that have lower TS, such as waste water or slurry. TS values are generally kept between 2-12%. Above this value, the material transfer is impaired (P.McKendry, SLR Consulting, 04/03/2008, personal communication). AD plants operating at much higher TS concentrations (i.e. over 40% TS for example) require different operational practices (Hilborn 2007) known as dry fermentation.

The volatile solids (VS) concentration of a particular feedstock is defined as the ability for the material to be biologically broken down by the bacteria. The VS is the organic fraction of the TS (Hilborn 2007). Therefore an increase in TS also increases the VS concentration, equating to a higher methane yield. For on-farm AD plants it is suggested that the VS concentration of feedstocks should be between 0.5 kg to 5 kg of VS per m³ of loading rate per day (Ecofys 2005). If this limit is exceeded the volatile fatty acids (VFA) limits will be exceeded. This increases the ammonia levels within the feedstock, which reduces the methane yield as ammonia acts as an inhibitor to this process (Chen 1983).

6.4.2 Feedstock type

The feedstock entering a digester system is ultimately the most critical factor in quantifying how much methane can be generated. In some cases the AD plant is designed before the feedstock types are chosen. Alternatively an AD plant is designed secondarily to the type of feedstock that is available. The benefit of the latter is increased efficiency within the process, whilst the first approach offers greater versatility.

In theory any organic material can be used for anaerobic digestion. This includes all biomass types such as crops, wood, excreta, etc. as long as they contain carbohydrates, proteins, fats cellulose and hemicelluloses as their main components (Deublein & Steinhauser 2008). However, the determining factor of the material choice is the rate of decomposition. Wood for example, has a very slow decomposition rate and therefore is generally not preferred in an AD process. For wood in particular, this is due to the high lignin content, which acts as an inhibitor to AD.

AD plants situated on or nearby sources of farm waste tend to use animal manure as the main source of feedstock. Liquid manure from pig and cattle waste is ideal for biogas generation as it has a relatively low TS concentration. Other liquid manures from sheep, horses and poultry waste can also be used. However, the TS concentrations for these are higher and they cannot be used solely as feedstock. The biogas yield from animal manure can vary significantly depending on the animal's feeding regime. Studies documented by Chen (1983) showed that ultimate methane yield for pig manure varied between $0.36 \text{ m}^3\text{CH}_4/\text{kgVS}$ to $0.53\text{m}^3\text{CH}_4/\text{kgVS}$, an increase of almost half. In general, animals fed on a high-grain diet produce a higher quality of methane per unit output of waste.

The ability of manure to degrade its organic substance is also affected by the animal that it originates from. The organic substance degradation (OSD) for cattle liquid manure is around 30%, whilst for pigs this rises to 50% and for poultry up to 65% (Deublein & Steinhauser 2008). This rise is proportional to the percentage of ammonia within the waste. Therefore a balance is required to obtain the maximum biogas available from the feedstock. Table 6-1, displays the TS concentration, VS concentration and typical biogas yields for a range of animal manure types.

Manure source	Total solids (TS) concentration	Volatile solids (VS) concentration	Biogas yield	Animal manure production
	%	%	m^3/kg of VS	$\text{m}^3/\text{day}/\text{animal}$
Dairy	12	10	0.1-0.8	0.05
Beef	8.5	7.2	0.3-0.8	0.055
Veal	5.2	2.3	0.24-0.4	0.008
Pig	11	8.5	0.3-0.8	0.0045
Sheep	11	9.2	0.3-0.4	0.006
Goat	13	9.5	0.3-0.4	0.006
Horse	15	10	0.4-0.6	0.033
Chicken	22	17	0.3-0.8	0.0001
Turkey	12	9.1	0.4-0.7	0.0002
Duck	31	19	0.4-0.6	0.0003

Table 6-1 Typical biogas yield of farm animal waste. Source: (ASAE 2003;Deublein & Steinhauser 2008)

Feedstocks which can boost biogas yield are called co-substrates. These are defined as a supplementary material to animal manure used within AD systems to improve the methane production. In general co-substrates have a higher TS and VS concentration and therefore are able to generate higher biogas yields. The use of these substrates is limited by the overall level of TS concentration at which the plant can operate.

Materials suitable as co-substrate include dedicated energy crops, such as grasses, cereals, vegetables and fruits, crop residues, straw and other vegetable wastes. Other non-plant co-substrates include animal waste other than excreta, consisting of blood, animal fat, bones and other slaughter house waste. Glycerine, the main by-product of biodiesel production can also have a very high biogas yield.

Digested waste from an AD plant is typically used as a form of natural fertiliser. The waste can only be classified as a natural fertiliser if it meets the Animal by-Product Regulations

(DEFRA 2008d). Adopting the use of co-substrates could affect the quality of the fertiliser and consequently various sanitation processes are undertaken to ensure the digestate conforms to these regulations. This includes pasteurization, where the waste is heated for one hour up to 70°C.

Typical co-substrate biogas yields along with total solids (TS) concentration and volatile solids (VS) have been displayed in Table 6-2. Comparing the two tables shows manures produce significantly lower biogas yields compared to co-substrates. In general, fats either from animal slaughterhouses or other animal waste processing, generate the highest biogas yields per unit weight of active ingredient (VS). Overall, feedstocks which have a high fat, carbohydrate and protein content will have a high biogas yield.

Co-Substrate	Total solids (TS) concentration	Volatile solids (VS concentration) as % of TS	Biogas yield
	%	%	m ³ /kgVS
Barley	23	85	0.8
Carrot	25	95	0.7
Fodder beet wet	18	87.5	0.7
Grass Silage	30.5	83	0.65
Hemp	92	90	0.7
Mangold	25	95	0.7
Maize	30	95	0.65
Oats	88	88	0.6
Ryegrass	20	95	0.7
Potatoes	25	79	0.8
Reed canary grass	20	90	0.6
Sugar beet wet	23	95	0.7
Sweet sorghum	26	93	0.8
Switch grass	37	93	0.8
Winter wheat	86	90	0.5
Rapeseed	92	92	0.7
Animal Fat	90	92	1.14
Fish Waste	26	80	0.9
Molasses	82	90	0.5
Glycerine	98	92	1.1
Fat and Flotation Sludge	24	98	1.2

Table 6-2 Typical volatile solids (VS) and total solids (TS) % along with biogas yield for potential AD feedstocks. Adapted from Deublein & Steinhauser (2008) and Martinez-Perez et al. (2007)

Biogas reactors can fail if overloaded with co-substrates. This is due to an imbalance between acid forming and methane forming microorganisms (Chen et al. 2008). Co-substrates also contain a number of inhibitors which can unbalance the operating conditions. Fats generate high levels of ammonia and long-chain fatty Acids (LCFA) which are both considered as biogas inhibitors (Chen et al. 2008).

6.4.3 Methane yield

The ultimate aim of a biogas plant is to maximise the methane yield based on the feedstock and the size of the plant. The methane yield is based on the retention time (RT) for which the

feedstock is processed, the specific methane yield of the feedstock and the loading rate of the feedstock. A simplified equation to determine the biogas production has been expressed by Ecofys (2005), as:

$$Biogas = [Manure \times TS \times VS \times B_o \times 1000] + [Co - Substrate \times TS \times VS \times B_o \times 1000] \quad 6-1$$

Where TS is the percentage of total solids within the material, VS is the percentage of volatile solids within the material. B_o is defined as the ultimate methane yield at an infinite hydraulic retention time. This can also be converted to the ultimate biogas yield.

Study of the kinetics of methane generation from fermentation show similar results as shown in equation 5-2. A model devised by Contois (1959) and also published by Chen (1983) showed that the methane yield from organic wastes could be accounted using:

$$\gamma_v = B_o L \left(1 - \frac{K}{\mu_m \theta - 1 + K} \right) \quad 6-2$$

Where, γ_v is the volumetric methane yield per m³ of digester volume per day; L is the VS loading rate per day, θ is the Retention Time (RT), K is the kinetic parameter relating to the performance of the digester and μ_m is the maximum specific growth rate of the microorganism (Chen 1983). B_o is the maximum theoretical methane yield, which can be obtained from literature or laboratory testing.

The maximum specific growth rate is the inverse of the minimum Retention Time (RT) required for the process to generate a sufficient quantity of methane. Therefore the minimum RT can be found by calculating the maximum specific growth rate μ_m . This parameter is linearly dependant on the operating temperature of the process. The Kinetic Parameter represents how efficiently the digester operates. It has been found that in some AD plants, high concentrations of volatile fatty acids (VFA) and ammonia hinder the digester performance. Experimental work highlighted by Chen (1983) showed that as the VS concentration increased the specific methane yield would decrease after a certain threshold was reached. This would vary for each particular plant setup.

6.4.4 Digestion operating temperature

Methane generation from AD can occur at temperatures ranging between 4-60°C (Price 1981). In practice there are three thermal categories at which digesters are designed to operate. These are thermophilic (40-60°C), mesophilic (30-40°C) and psychrophilic (below 30°C). Thermophilic digesters produce the highest methane yield; however have a larger heat energy requirement. Most AD plants in Europe operate within the mesophilic range (Ecofys 2005; Price 1981). Thermal pre-treatment is also common on some AD setups which help sterilization and odour control of the feedstock (Price 1981).

6.4.5 Retention time

The hydraulic retention time (HRT), also known as the residence time is the period in which the feedstock is processed within the digester. During this time methane is generated and stored in a separate storage unit. The value of HRT can be determined from the inverse of the specific growth rate (μ_m). The optimum HRT is dependant on the operating temperature. As a result it can also be grouped into three process ranges similar to that of operating temperatures. For psychrophilic process, the HRT can be between 40-100 days, for mesophilic the HRT is between 35-40 days, whilst for thermophilic process the HRT is reduced to 15-25 days (Ecofys 2005).

6.4.6 Other parameters

Other significant parameters included the specific surface area of the material. According to Deublein & Steinhauser (2008), biogas yields can improve by 12% if the surface area of the material is increased. This is often carried out by macerators. These devices powered by electric motors are able to reduce particle sizes to around 12mm in diameter.

The process of AD must also be undertaken with minimum (or no) light as this is an inhibitor in the methanation stage. Other factors required to maintain steady and efficient operating conditions include the pH level, which should be kept between 6.5 and 7.5. The carbon to nitrogen ration (C/N) should also be maintained at around 16:1 to 25:1. Too low a value increases the ammonia production because nitrogen levels become too high (Deublein & Steinhauser 2008).

6.5 Analysis of anaerobic digestion plants in Europe

An assessment of some performance parameters was carried out using a number of AD plants situated in Germany. The AD setups varied in digester size from less than 200m³ to around 9000m³. From the data, a number of correlations were determined, which have been detailed in the following sections.

6.5.1 Biogas yield vs. total digester volume

The graph in Figure 6-3 shows the methane yield vs. total digester volume for a number of plants. The methane outputs were generated from a range of digestible materials. The graph shows that methane yield is roughly linearly proportionate to the digester volume.

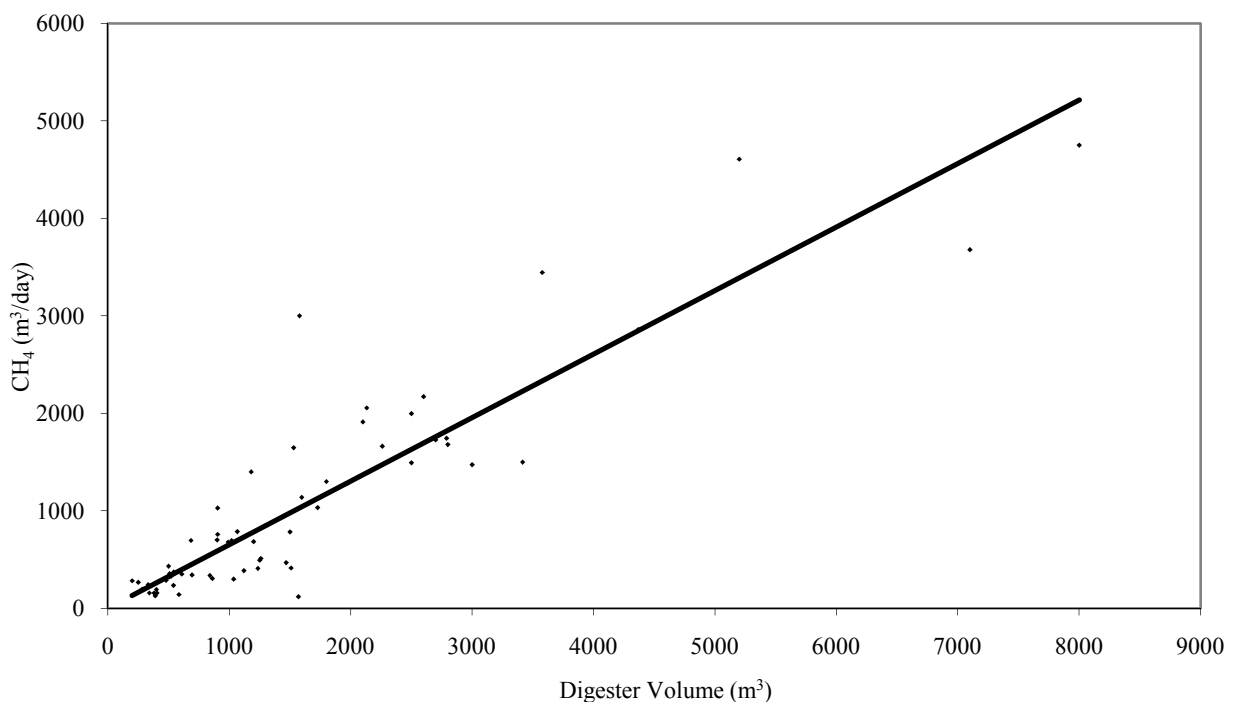


Figure 6-3 Relationship between methane production rate and digester volume for mixed wastes: Data from FNR (2005)

The linear regression was found to be relatively low (0.8) indicating that there was a significant element of error within the results. This was contributed to a number of factors. The most critical factor was the feedstock used within the AD plants. The AD plants operated on a primary feedstock of cattle and pig waste. However other wastes were also present, including: glycerine, vegetable waste, fats etc. This significantly altered the biogas yield as the addition of a co-substrate generated a higher gas yield when fermented.

Other contributing factors to the non-linearity of methane yield vs. digester volume included the set-up design of AD plants. A number of the plants analysed operated using either single stage, or multi-stage digester system. In AD plants with one single digester the four anaerobic digestion phases (hydrolysis, acidogenesis, acetogenesis and methanogenesis) took place simultaneously in one single reactor. However to improve efficiency and increase the use of a co-substrate, multi-stage or more commonly 2-stage reactor designs are chosen. These include two separate reactor tanks. In the first tank the hydrolysis and acidogenesis takes place, whilst the second reactor tank houses the acetogenesis and methanogenesis stages.

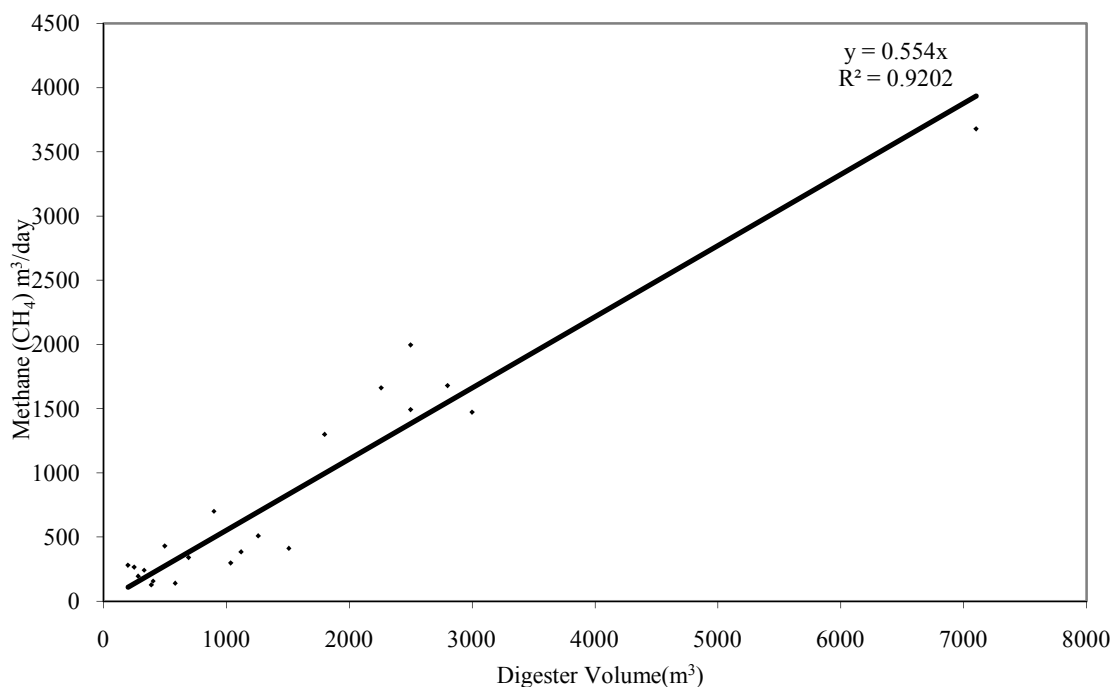


Figure 6-4 Relationship between methane production/day and digester volume for cattle waste only: Data from FNR (2005)

By assessing AD plants with 90% or more cattle waste feedstock (Figure 6-4), a clearer correlation was seen between the digester size and the methane yield. The linear regression is within a more acceptable range for deducing an accurate estimate between the digester volume and the expected methane yield. As predicted, the methane yield is slightly lower for cattle waste than for mixed waste, due to the improved performance characteristics of co-substrates which enhance the methane yield.

6.5.2 Other correlations determined between performance parameters

The analysis attempted to highlight a link between the methane yield per unit weight of input material and the hydraulic retention time (HRT). For single stage AD plants there was a correlation between the increase in methane yield per tonne of substrate and the HRT, as shown in the Figure 6-5.

Although the data showed a deviation, the results in Figure 6-5 show that as the HRT increased the overall methane yield per tonne of substrate also increased. This was caused by allowing the material to complete a longer digestion time and hence recover more methane. Therefore a longer digestion time is preferable in maximising methane yield. However, as can be seen from the study of Karim et al. (2007), as the HRT is increased the rate at which methane is produced is significantly reduced, as shown in Figure 6-6.

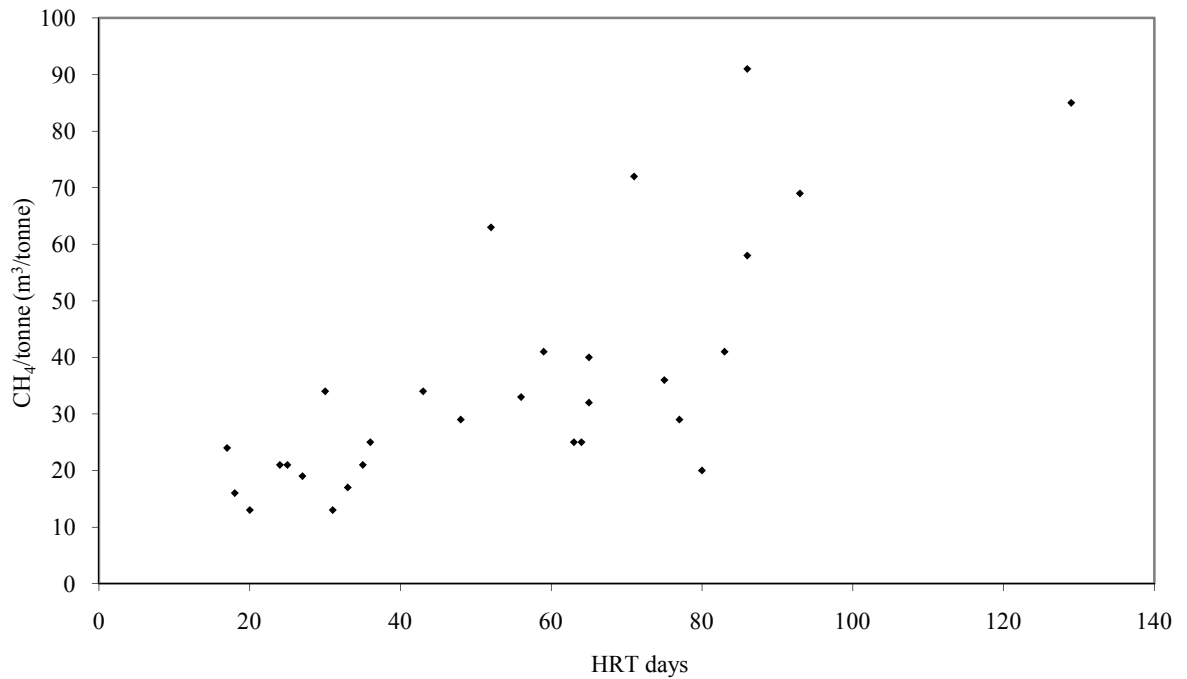


Figure 6-5 Methane output per unit weight input vs. hydraulic retention time (HRT): Data from FNR (2005)

As the methane production rate reduces with time, an optimum digestate removal time has to be determined to ensure the plant efficiency is high. Attempting to recover a small percentage of the remaining available methane over an extended period of time may be more costly and less time effective than removing the original waste and replacing it with fresh waste with higher methane production rates.

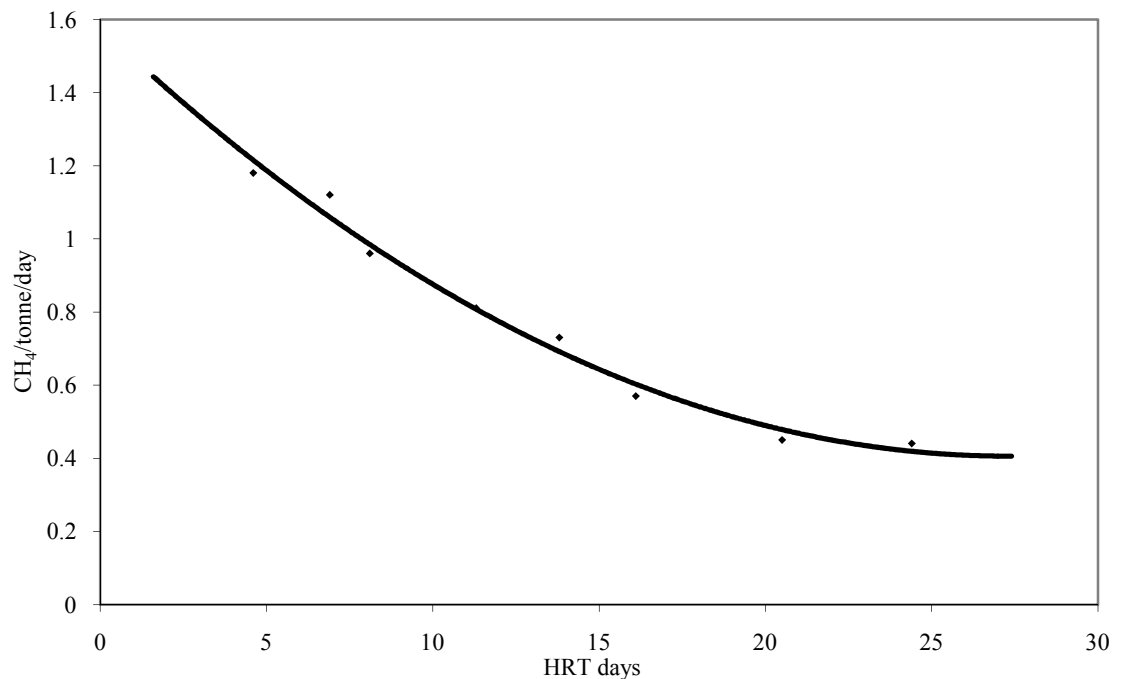


Figure 6-6 Experimental findings of methane production vs. HRT from Karim et al. (2007)

The rate at which the methane is produced is also dependant on the reduction in VS concentration during the AD process. This is the conversion efficiency of the process. Typical AD plants aim for a conversion efficiency of around 70-80% (J.Gascoigne, Greenfinch 05/05/2008, personal communication). If 100% conversion efficiency was achieved then all the possible available methane would be extracted. The longer the HRT, the higher the VS reduction rate will be. The graph shown in Figure 6-7 highlights how the VS reduction efficiency varies with the methane yield per tonne of input.

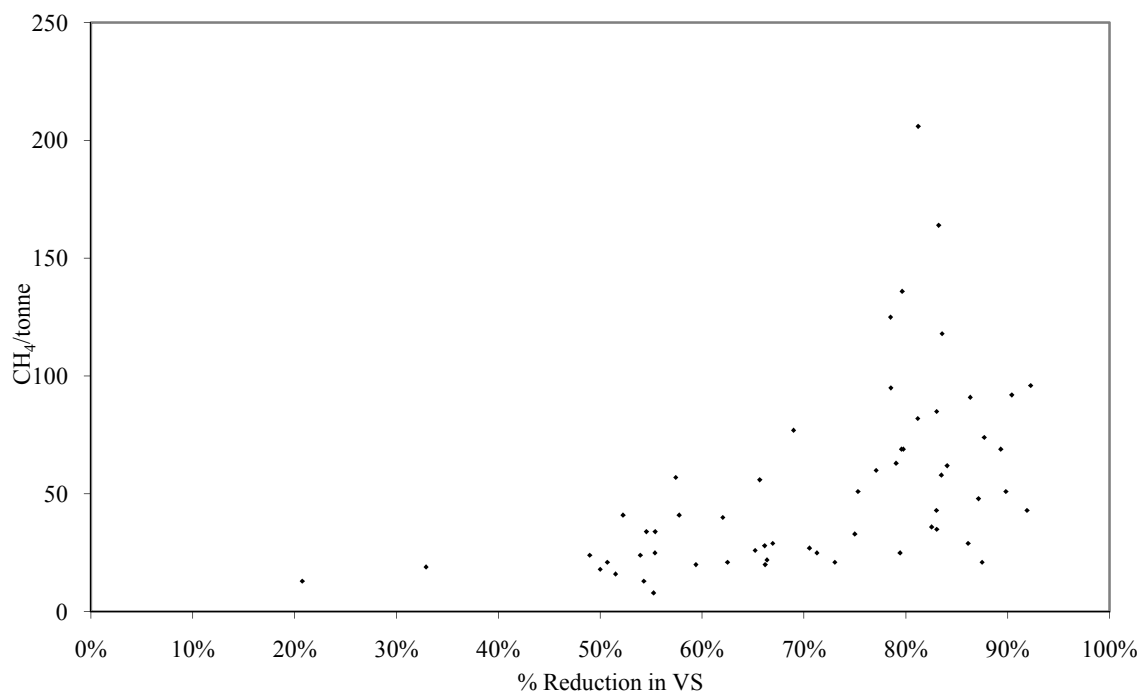


Figure 6-7 Methane output per unit weight input vs. VS reduction: Data from FNR (2005)

The results in Figure 6-7 show that as a higher VS reduction is achieved, the methane yield per tonne of input also increased. However as can be seen from the data, this is also subject to a large error allocation and no clear linear regression could be obtained. This is due to the varying HRT which could affect the VS reduction efficiency.

6.6 Concluding remarks

There are a number of process parameters which have an impact on the performance of AD. To understand the performance of AD, the kinetics of bacterial growth has been considered, assessing the work of Chen (1983). From this mathematical modelling an appreciation of how the methane generation was linked to HRT, the operating temperature and the kinetic parameter. The kinetic parameter in turn, was also affected by the organic loading rate of a digester. Given this understanding, the operational performance of existing AD plants within Europe could be analysed. Trends between the methane yield and the digester input, the HRT and the VS reduction rate were found. The following stages of the research use the information gathered within this chapter and assess the potential of biogas for the South West of England. The appraisal techniques used in the following chapters build on this knowledge as it forms the foundations of the study. A study of this nature has been essential in appreciating the complexity of AD for biogas production.

7 ENERGY ANALYSIS OF BIOGAS

This chapter reports the work carried out in analysing the potential of biogas production using energy analysis techniques, described in Chapter 5. The aim of the chapter is to summarise the critical factors affecting the energy inputs and outputs of biogas production, followed by an analysis of existing operational biogas plants.

Throughout the chapter, reference will be made to data from currently operational AD plants (also denoted as German AD plant data). Some of this data has been kindly supplied by Mark Patterson from Fachagentur Nachwachsende Rohstoffe e.V. (FNR), the German Agency for Renewable Resources (FNR 2005). This dataset consists of extensive operating data for 61 anaerobic digestion plants of varying size and feedstock.

This data was used to show correlations between AD performance parameters on an energy analysis basis. Using these results, three AD plant case studies were examined in detail and a complete energy analysis was undertaken. However, wherever possible, actual plant data was used; collated from various AD plant visits (J. Gascoigne, Greenfinch 05/05/2008 personal communication; J. Prior, Summerleaze Ltd. 22/05/2007, personal communication).

7.1 *Motivation for study*

Studies on the performance of biogas production from AD have been found to fall into two main categories. These are the studies of kinetics of microbial growth for methane production and the high-level plant design/energy studies of AD. The major studies discussing kinetics of microbial growth were developed during the late 70s to early 1980s and have been discussed in Chapter 6. These studies were a result of a surge of interest in AD technology as a possible displacement solution to the (at the time) sudden rise in cost of fossilised fuels. Within the last decade however, greater focus within research has been on optimising plant design, layout, feedstock and overall- energy output (Berglund & Borjesson 2006; Gerin et al. 2008; Ghafoori & Flynn 2007).

Energy analysis and AD plant design optimisation has shown that the process of biogas production is greatly affected by feedstock type and availability. Due to the nature of biogas production from AD it is difficult to represent a single result for net-energy analysis. This is because feedstocks react differently in different setups at different temperatures and therefore often there is little or no uniformity between results. If the net-energy balance were found, then a list of assumptions on system boundaries, ambient conditions and process layout would also have to be shown.

Analysing published literature on net-energy analyses of biogas has shown a wide range of results; which is expected as AD setups can be very diverse. Biogas production from maize silage was found to require 0.04-0.14 MJ of primary (or resource) energy per MJ of energy output (also interpreted as the ERE) (Gerin et al. 2008). However, decomposing grass for biogas was found to require as little as 0.013-0.03 MJ of primary energy per MJ of energy out. The very high energy output of grass from biogas could be a reason why grass silage is present in many German AD plants (FNR 2005).

A net-energy analysis was carried out on a number of different feedstocks for Swedish setups in 2006 (Berglund & Borjesson 2006). They found that the energy requirement for energy (ERE) for biogas using grass was around $0.14 \text{ MJ}_{\text{resource}}/\text{MJ}_{\text{delivered}}$. The study assumed a feedstock transport distance of 10km. These energy inputs were more apparent for the net-energy analysis of low biogas-emitting feedstocks such as manures (*ibid*). Due to the larger energy output of high biogas-yielding feedstocks such as maize or grass, the energy requirements for transport would become less significant.

Energy analysis has also been used to determine the optimal size of an AD biogas production plant. However the main conclusions from the study appeared to be that the optimum size was greatly dependant on the local availability of feedstock (Walla & Schneeberger 2008). The aforementioned study calculated the optimum size to be between 575kW_e to 1150kW_e. However, these results were linked to financial investment support available and not just the energy output in relation to energy input.

A common element across many studies is that the ERE can be affected by the transport distances of the feedstock to and from the AD plant. Generally, this is true for all bioenergy feedstocks due to the relatively low energy densities of the material. As a result, transporting feedstock can increase the ERE of biogas fuels (Areikin & Turley 2008). This study attempts to understand the energy costs in terms of ERE due to the transportation of feedstocks for biogas production.

The net-energy of biogas production is therefore rather more complex than some more simple renewable energy systems. All bioenergy systems require operational energy requirements in order to produce energy. This is unlike any other form of renewable energy such as solar photovoltaic and solar hot water, wind or geothermal. Bioenergy systems, such as biogas require energy inputs, which can depend on fossil fuels used, the feedstock extraction, feedstock processing, transport (and associated losses) and conversion efficiencies. These energy inputs in turn can have a large variability depending on the setup of the biogas production plant.

As a result, 'simple' renewable energy systems such as photovoltaic or wind turbines appear to have extensive data on comparative net-energy analyses from a wide range of studies (Allen et al. 2008a). The few studies, which ultimately show the net-energy analysis of biogas also incorporate error margins which can affect the results. This study highlights the importance of analysing biogas production using existing operational plants where energy inputs, transport distances and actual performance data are present. This study therefore examines the energy-analysis of a range of existing operational AD plants.

7.2 *Energy requirements for biogas production*

The energy requirements for biogas production account for all the direct and indirect energy inputs into the AD process. Previous studies have shown that operational energy inputs could reach up to 80% of the total energy outputs of AD plants (Borjesson & Berglund 2006). The importance of operational energy inputs signifies that all energy expenditures, including feedstock transport and crop growth should be analysed. This analysis examines the trends in heat and electrical energy consumption for a number of existing AD plants, along with a

review of the literature surrounding these energy uses. Additionally, this study investigates the energy requirements for plant construction. This is an energy input which should be assessed, in accordance with standard procedures of energy analysis (IFIAS 1974).

7.2.1 Plant construction energy input

The design of an AD plant has been discussed in Chapter 6. The AD unit is a combination of vessels, pumps, motors, tubes and peripheral materials, which are determined by the ambient conditions, the feedstock digested and the size of the plant. This study examined standard Continuously Stirred Tank Reactor (CSTR) systems, as this was the most common plant design.

The most common construction material used for AD plants is steel; however, some plants employ concrete or even polymer materials for the primary components (Ecofys 2005). The primary components (in terms of material use) of AD plants are the feedstock tanks. A description of a typical AD plant has been produced in section 8.6. Structurally, most CSTR plants are similar in construction and as a result, material analysis from the case study plant A was used in this section. This was due to having obtained detailed material requirements for the construction (J. Gascoigne, Greenfinch 05/05/2008 personal communication). This data was due to site visits and communication with the plant operator. The use of LCA software SimaPro was used to calculate the total embodied energy of the AD plant construction. Using the EcoInvent database (Swiss Centre for Life Cycle Inventories 2007), the cumulative energy demand of the construction materials was calculated.

Plant components	Embodied energy (MJ)
Digester tank	886,689
Digestate tank	1,320,357
Reception tank	243,970
Biogas storage tank	7,748
Heat exchanger unit	143,421
Stirring device	28,288
Auxiliary equipment	8,410
Digester pre-heat	7,109
Digester heater	7,109
Other	1,826
TOTAL	2,654,925

Table 7-1 Total embodied energy (primary energy) required for AD plant manufacture

The breakdown of embodied energy of the AD plant is shown in Table 7-1, showing the total embodied energy for the manufacture of the plant to be around 2,650 GJ of primary energy. The embodied energy was calculated using all the direct and indirect processes required for plant manufacture, which have been discussed in section 8.6.1. The embodied energy procedure calculated the total (primary) energy use through a life cycle, based on the calorific value of fuels. The cumulative energy demand (CED) determined all the energy sources required within the manufacturing stages.

The CED process accounts for all electrical, heat and other process energy requirements up to the point of material use. The energy was then converted to its primary resource form based

on primary energy conversion efficiencies for typical energy forms. For example, in the UK current electricity is produced using a mixture of coal, gas, nuclear, hydropower, oil, natural gas and renewable energy. This composition was determined using the latest statistics from BERR (2008a). The primary energy inputs were determined from the source (*ibid*) and inputted into the life cycle of the plant manufacture.

7.2.2 Heat energy consumption within an AD plant

This part of the study assessed the factors which affect the heat energy requirements of AD plants. Using data from German operational AD plants, it was possible to examine a number of parameters which could affect heat energy requirements (FNR 2005).

Although the process of anaerobic digestion is exothermic, the actual heat produced is negligible, thus source heating is required to operate the process. Depending on the operating temperature range (mesophilic, or thermophilic) and the ambient temperature, different levels of heat energy are required (Ecofys 2005). Operating temperatures can be as low as 25°C, which during UK summer periods of the year result in a lowered heat energy demand within the AD plant. However, if operating temperatures of 40°C (thermophilic) are required, then heat energy demand can increase. In this energy analysis, a standard operating temperature of 39°C was selected, as this was the operating temperature of the AD plants investigated (FNR 2005).

Heating of the digestate is required to accelerate the anaerobic digestion process (Deublein & Steinhauser 2008). Insulation is generally used to maintain a constant temperature and reduce energy losses. In the UK, climatic temperatures usually fall below the operating temperatures of an AD plant, as shown in Figure 7-1. Seasonal variation can affect the processes' heat energy requirements if insulation is not effective. The average monthly temperature recordings of a typical location in the South West (Yeovilton 1971-2000) have been shown in Figure 7-1. The temperature can vary by up to 15°C depending on the season and this can be a significant contributor to the heat requirements of an AD plant.

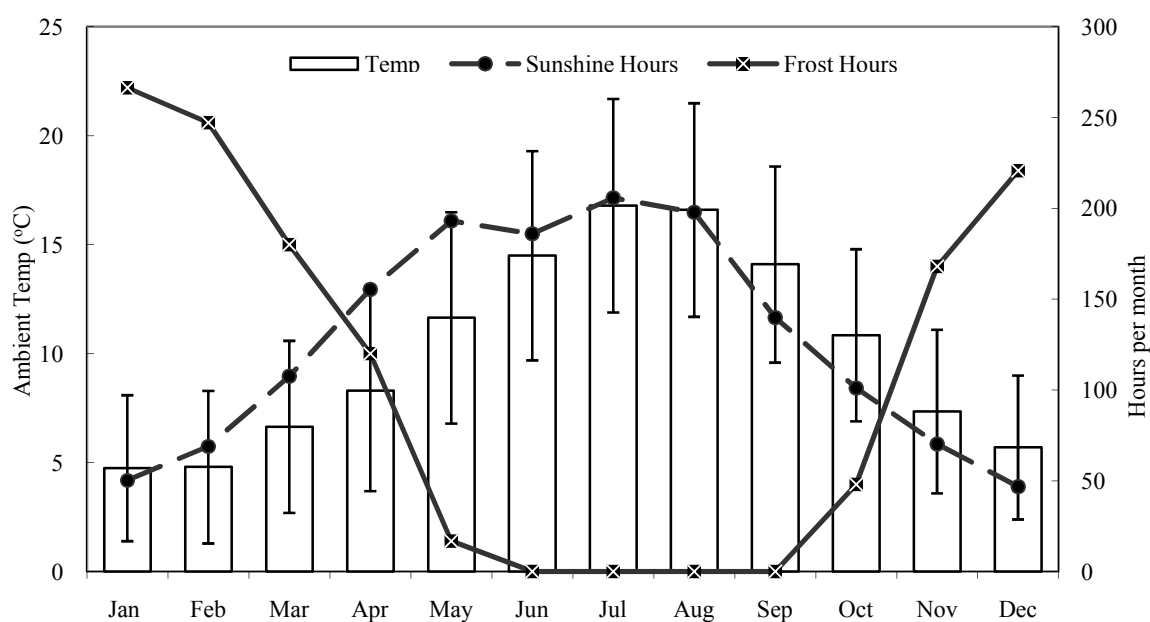


Figure 7-1 The typical ambient temperatures during the year for Yeovilton (Met Office 2007)

Heat energy is supplied through various techniques depending on size and setup of the AD plant. On small-scale plants the heat is transferred to the feedstock through heat exchangers and then pumped around the digester (J. Gascoigne, Greenfinch 05/05/2008 personal communication). Larger setups adopt heating pipes or coils within the digester wall (Ecofys 2005). It is reported that around 11-15% of the total biogas energy produced is used for heating feedstock entering the AD plant (Deublein & Steinhauser 2008). However, recordings from existing operating plants showed that heat energy requirements averaged around 24% ranging from 1.8%-65% of the total energy production (i.e. the ERE) (FNR 2005).

Solar gain is considered a critical aspect of heating for AD plants. As can be seen in Figure 7-1, the operating temperature can be only 10-20°C higher than summer average ambient temperatures, in order to reach 39°C. The heat energy requirement is therefore reduced at higher levels of solar gain (El-Mashad et al. 2005). One of the most critical factors affecting the heat energy consumption is the energy lost through the digester walls (Ecofys 2005). The overall heat transfer coefficient of the digester is dependant on the material used for the digester insulation. These have been shown in Table 7-2, with their respective U value and the typical thickness adopted within an AD setup.

Insulation Material	U W/m ² K	Common Thickness (Metres)
Polyurethane	0.03	0.06
Expanded Polystyrene	0.04	0.08
Extruded Polystyrene	0.035	0.08
Mineral Wool	0.043	0.1
Cork	0.05	0.1
Sheep Wool	0.035	0.1

Table 7-2 U value (thermal conductivity) for different insulation materials (Ecofys 2005)

Another factor affecting the plant heat energy consumption is the initial start-up fuel used to heat the digester in order to initiate the anaerobic digestion reaction. The data obtained from case study plant A showed an annual heat energy consumption of 226 GJ. Approximately 23% of this heat energy was obtained from kerosene during the start-up phase, whilst the remainder was obtained from the excess biogas. This value resulted in an energy consumption of 346 MJ/tonne of feedstock. The value was found to be very similar to other studies (Berglund & Borjesson 2006), if kerosene energy consumption was removed. This suggested that start-up energy requirements might not have been taken into account within other studies as no mention of start-up energy was found.

By analysing the currently operational German AD plant data (FNR 2005) a correlation was found between the heat demand (MJ/day) and the feedstock input quantity (cubic metres/day). As the feedstock input increased, the energy consumption (MJ/day) increased by just over 4.7MJ/day per tonne of feedstock. To determine the dependency of this parameter on the total heat energy requirements, a number of factors were assessed using the 'power-law' correlation, common amongst practitioners of engineering and physical sciences (Cranston et al. 2007;Hammond 2006). Subsequently, a logarithmic plot of heat energy requirement vs. quantity of feedstock showed a very strong correlation between these two parameters (close to a power of 1). The power value signifies the influence which the parameter has on the heat

energy requirement. A value close to one is very influential, whilst a value of one is completely influential.

In order to determine the empirical coefficients of this expression, data from over 60 AD operating plants were used. The quantity (tonne/day or m³/day) and the change between operating and ambient temperature was assessed, using available data. An average ambient temperature of 15°C was used. Using the power-law correlation detailed in Appendix A, the results highlighted the strong dependence of heat energy requirement on the feedstock input quantity within the AD plant.

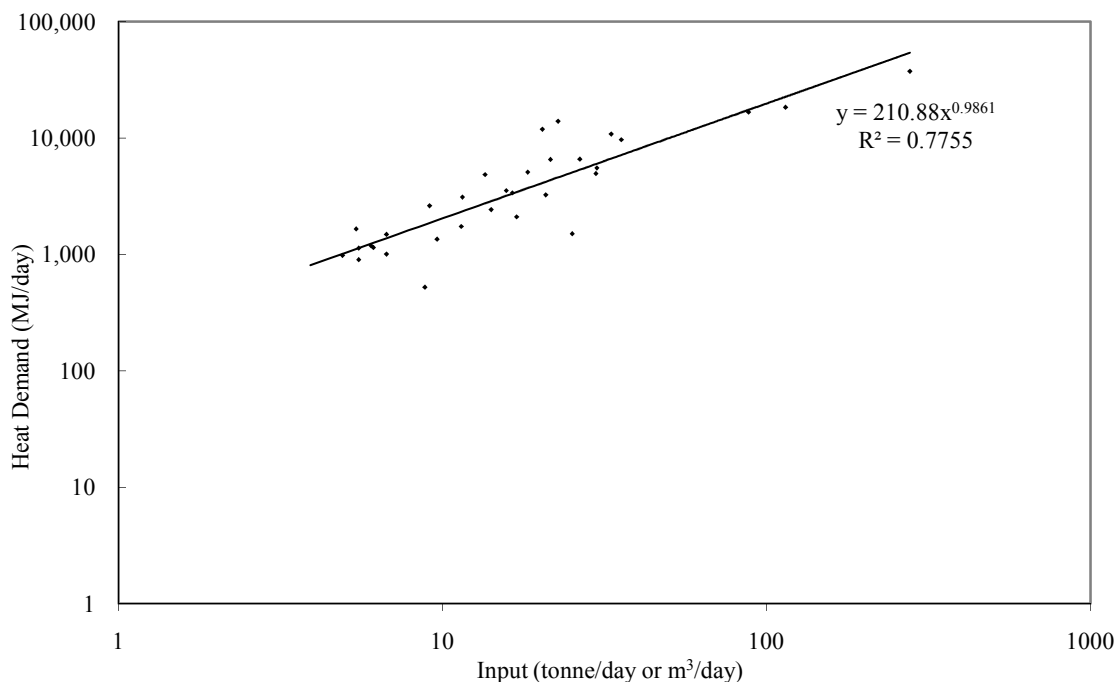


Figure 7-2 Heat demand per day vs. input feedstock per day (using log-scale)

A correlation was found between the feedstock input into the AD plant and the heat energy consumption. Using this correlation (shown in Figure 7-2), the heat energy requirements for the three AD plant case studies were calculated, where this was not previously available from existing plant operating data. This data was subsequently used for all the multi appraisal techniques.

7.2.3 Electricity consumption within an AD plant

In addition to the heat energy input required to maintain the AD process, electricity inputs are needed to operate pumps, stirring devices and other components. Feedstock is circulated around the AD plant, enabling it to enter and exit a number of processes in the course of biogas production. It is important to ensure the waste is relatively free flowing with a maximum total solids (TS) concentration of only 12-14%. Centrifugal pumps are used for pumping waste around the AD plant. These have a high efficiency and are relatively easy to maintain. A macerator is also used to reduce the particle size of the waste.

Agitation of the waste in the digester is undertaken to ensure heat is received throughout the whole process and this increases the efficiency of the biogas production. The feedstock mixing system uses electrically powered motors for either paddle stirrers or pumps. Submerged propellers tend to use between 2.5kW and 25kW. They are active for half of the operation time on an intermittent basis (Deublein & Steinhauser 2008).

One of the case studies used within the appraisal methodology (plant A) had a recorded electrical energy consumption of 4.29 kWh/tonne (15.4 MJ/tonne). Whilst data from currently operational plants determined that on average 12.4 kWh of electrical energy was used per tonne of input feedstock (FNR 2005). This included all electrical energy in stirring, pumping and peripheral equipment. However, the difference between the maximum and minimum value was 32 kWh/tonne (maximum electrical energy consumption = 33 kWh/tonne, minimum = 1 kWh/tonne). As data variation was so elevated, a relationship between the plant operating parameter and electrical energy consumption was found.

A power-law correlation between the electricity consumption and the dependant parameters was performed, due to the number of parameters affecting the electrical energy consumption. Electricity consumption within a plant was suggested to depend on the digester volume (and related to daily feedstock input) and the material flow characteristics; represented by the TS % (Deublein & Steinhauser 2008). This is shown through an initial relationship, below:

Biogas electrical energy requirement (E_r) = function {feedstock quality (TS), quantity of feedstock (M)};

The above relationship can be converted into a power-law correlating equation in common with practice in the engineering sciences (Hammond 2006):

$$E_r = \text{Constant } \{TS^w M^x\}, \quad 7-1$$

The most critical parameter to electrical consumption was found to be the percentage of dry matter (TS) of the input material (a power-law dependency of around 2/3), shown in Figure 7-3. Although the parameter was found to have a relatively high influence on the electrical energy demand, the analysis also showed that the square of the Pearson Product-Moment Correlation coefficient (R^2) was relatively low at 0.55, thus resulting in a large standard deviation from the mean. This was thought to be related to the type of mixing system used within the plants. Some digesters operated using single stage and other on two or three stages. This would influence the energy consumption for stirring and heating.

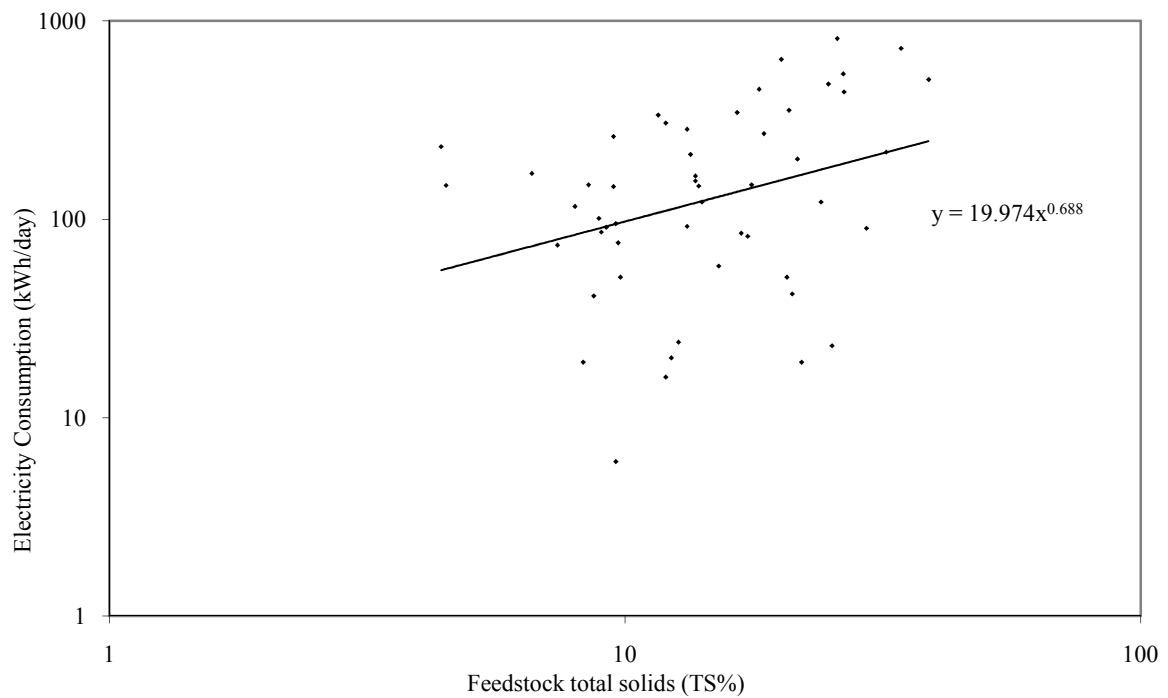


Figure 7-3 Electricity consumption per day vs. total solids (TS %) of feedstock

Figure 7-3 demonstrates a relationship between the material composition and the electrical energy required within the plant. The analysis was extended to single stage digesters only. Carrying out a similar analysis highlighted a closer link between the TS percentage and the electrical energy consumption per tonne of feedstock ($3/4$ rather than $2/3$).

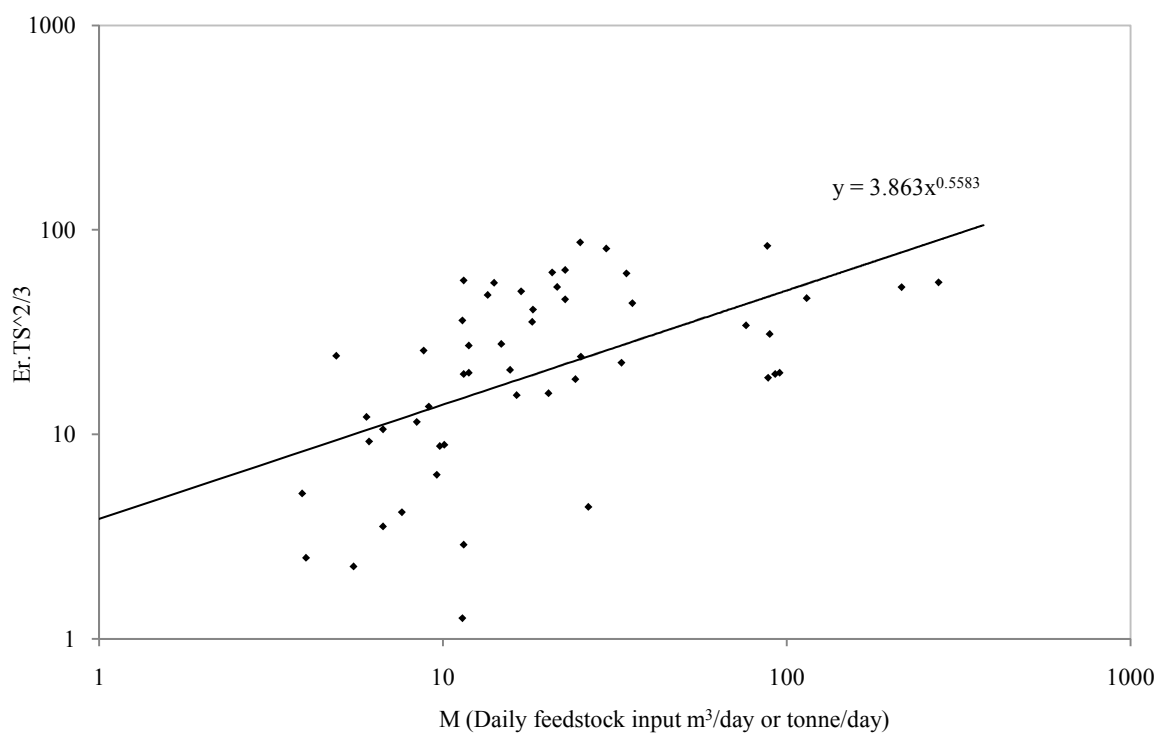


Figure 7-4 Logarithmic plot of Er multiplied by $TS^{2/3}$ against daily feedstock input

The study was also extended to assess the relationship between electrical energy consumption and the amount of feedstock digested. The power constant of this relationship was determined by plotting the combination of $TS^{2/3}$ and Er against the feedstock input (M); shown in Figure 7-4. This can be shown in the equation below:

$$Er.TS^{-2/3} = M \quad 7-2$$

The correlation was plotted on a logarithmic scale. The power constant found and showed in Figure 7-4, was the power law correlating factor between daily feedstock input (M) and the electrical energy consumption (Er). The power law was $14/25$ (0.556) and the constant found to be 3.86. Therefore the new equation can be shown as follows:

$$Er = 3.86(TS^{2/3}.M^{14/25}), \quad 7-3$$

The analysis highlighted that the electrical energy consumption within the plant was influenced primarily by two parameters: total solids of material (TS %) and the daily feedstock input. The analysis has helped understand how the feedstock parameters influence the electrical energy consumption within AD plants. The electrical energy data for the three AD plant case studies was already known; subsequently actual operating data was used.

7.2.4 Transport energy use

The energy consumption during the transport of the feedstock to and from the digester plant can have a significant impact on the net-energy of a biogas plant. During contact with an AD plant operator (J.Prior, Summerleaze Ltd. 22/05/2007, personal communication), it was highlighted that feedstock could travel great distances depending on the quality of the feedstock. In this particular case, the feedstock glycerine was being transported from Scotland to the South West of England, a distance over 500 miles. Assuming a 20 tonne lorry was used to transport the feedstock, this results in approximately 11 MWh (37.3 GJ) of energy; equivalent to 956 m³ of methane production.

Large-scale AD plants tend to operate on a variety of organic waste feedstock types. These may include municipal solid waste, waste from the food industry, sewage waste and dedicated energy crops. This is partly due to the scale of the plant requiring significant quantities of waste consistently, which cannot be supplied from farmers. However, more importantly other organic wastes are chosen due to the financial incentives available, such as the landfill tax avoidance discussed in Chapter 3.

A study of published literature (Areikin & Turley 2008; Berglund & Borjesson 2006; Walla & Schneeberger 2008) showed that transport energy consumptions are primarily dependant on the bulk density of the feedstock being transported and its quantity (*ibid*). Typical energy consumptions for truck transportation of animal manure are suggested to be approximately 1.6 MJ/tonne/km, whilst for crops this reduces to around 1.1 MJ/tonne/km (Berglund & Borjesson 2006); therefore dependant on the truck loading.

Due to the high moisture content of manure, the average density for these feedstocks is around 1000 kg/m³. If this feedstock were to be transported using a typical vehicle of 22.5

tonne capacity (20m³ volume maximum capacity), the laden weight of the manure would be close to 100%, based on fuel consumption literature as shown in Table 7-3 (Areikin & Turley 2008).

	Weight laden %	Fuel use litres/km	Energy use MJ/ km
Articulated Vehicle 22.5 tonne capacity	0%	0.311	10.885
	25%	0.345	12.075
	50%	0.379	13.265
	75%	0.414	14.49
	100%	0.448	15.68

Table 7-3 Transport energy consumption. Source (Areikin & Turley 2008)

Crops such as oats, barley and wheat are reported to have a bulk density of 700 kg/m³ (Halliday et al. 1995). Therefore, a total vehicle loading of around 62% would be expected. This was found to use between 13.3 MJ to 14.5 MJ per kilometre travelled. Dryer materials were found to have a lower density, whilst manure with a very high moisture content, had a higher density, subsequently requiring more energy per m³ for transportation.

The use of manure for biogas production offers a lower gas (and energy) yield compared to crops such as oats, maize, grass etc. (Ecofys 2005). It is evident that manure is limited in transportation distance, as it would subsequently become energy negative: i.e. the invested energy in obtaining biogas would be greater than the biogas energy content. Energy crops, fats and glycerine types of feedstocks can travel much greater distances while remaining energy positive as the energy yields of these feedstocks are much higher. It has been reported that maximum distances for manures to be transported are in the region of 120 miles, whilst high yielding feedstocks such as fats and other animal wastes can be transported up to 470 miles prior to becoming energy negative (Berglund & Borjesson 2006). Consequently it can be said that AD plants operating using manures may have a higher ERE than those using high biogas-yielding feedstocks.

The three case studies in this study adopted different transport distances. Plant A was situated inside the farm where the feedstock was produced; as a result no transport energy was required. However, according to Spielman et al. (2007b), onsite waste handling equipment (such as a mini-digger or tractor) for AD plants is estimated to consume around 18MJ/tonne. Subsequently, this energy use was accounted for. As plants B and C were of larger scale, they both required energy use to transport the feedstock to the AD plants. Using transport distance data from Cumby et al. (2005) for plant B, this was converted to an energy value and correlated for the feedstock quantity in plant C.

7.2.5 Feedstock growth and collection stage

There are two main sources of feedstock for anaerobic digestion; animal manure and co-substrates. The energy inputs for animal manure include the waste collection from indoor animal housing units and energy expended for loading in tankers or containers (J. Gascoigne, Greenfinch 05/05/2008 personal communication). Dedicated energy crops, as shown in Table 7-4, are more energy intensive. If a crop is grown specifically for biogas production, then the

energy required to grow the crop should be included within the energy analysis. This differs from animal waste sources, as the purpose of the animal is not for energy production.

Energy consumptions per hectare of material grown were recorded for a number of crops. These were obtained from various literature sources (Deublein & Steinhauser 2008; Ecofys 2005; Gerin et al. 2008; Martinez-Perez et al. 2007). Energy consumption for growing crops included ploughing, seeding, sowing, fertiliser inputs, harvesting and collection and transport of harvest. The results were obtained in MJ/ha, although these were subsequently converted to MJ/tonne or MJ/m³ of crop used for coherence with the rest of the study, as shown in Table 7-4.

Crop	Crops grown in SW (DEFRA 2007b)	Energy per ha	Yield	Crop production energy requirement
	ha (2007)	MJ/ha	tonne/ha	MJ/tonne
Barley	94,677	16,563 ^a	5.9 ^c	2,807
Fodder beet	5,286	18,247 ^a	120 ^d	152
Maize	58,510	17,630 ^a	9 ^c	1,959
Oats	21,443	15,094 ^a	6.2 ^c	2,435
Potatoes	6,996	48,200 ^a	44 ^c	1,095
Sugar beet	618	21,400 ^a	50 ^d	428
Wheat	172,045	23,920 ^a	7.8 ^c	3,067
Rapeseed	52,177	11,645 ^b	3.2 ^d	3,639

^a (Martinez-Perez et al. 2007), ^b (BERR 2003), ^c (Nix 2009), ^d (Soffe 2003)

Table 7-4 Energy consumption per ha and per tonne for feedstocks grown in the SW

The table shows crop production energy use per tonne of oilseed rape and wheat were amongst the highest. This was a result of the relatively low yield in terms of tonne/ha for oilseed rape, whilst energy use per hectare for wheat production was amongst the most intensive. This high energy consumption was due to large fuel consumption for preparation, sowing and harvesting including energy use associated with herbicide, insecticide and fungicide control (BERR 2003). However, energy intensive crops such as oilseed rape and oats also generate a high maximum methane production, therefore allowing them to be transported over larger distances and validate the expenditure in growth energy.

In this analysis, the case studies plant A and B did not have any energy expenditures in terms of feedstock production. This was because both of these plants operated on waste-derived feedstocks. Plant C used maize silage as a supplementary feedstock (co-substrate) and as a result had energy expenditure for feedstock production. The quantity of co-substrate was obtained from plant operating data (FNR 2005) and applied to the corresponding value shown in Table 7-4.

7.3 Energy output of AD plants

The output energy of an AD plant is directly linked to the methane production. Estimating energy outputs based on a theoretical analysis of methane yield was found to be inaccurate and not advisable for mixed feedstock wastes (Chen 1983; Ecofys 2005; Chen & Hashimoto 1978). However, it is important to understand the parameters affecting biogas output and how these affect the energy balance of AD plants.

The study of kinetics for methane generation is widely documented and has been addressed in a number of literature sources throughout the past 50 years (Chen & Hashimoto 1978; Chen & Hashimoto 1980; Contois 1959; Hill 1983; Karim et al. 2007; Linke 2006). This theory has been discussed in Chapter 6.

To calculate the energy output from biogas, a net calorific value (CH_{4CV}) of 35.8 MJ/m³ was used for methane (CH₄) at standard pressure and temperature (Ecofys 2005). The energy available from the biogas can be calculated using:

$$Energy(MJ) = CH_4(m^3) * (CH_{4CV}), \quad 7-4$$

In an energy context, the overall methane yield from organic wastes can be expressed by:

$$\gamma_v = B_o L \left(1 - \frac{K}{\mu_m \theta - 1 + K} \right), \quad 7-5$$

Where, γ_v is the volumetric methane yield per m³ of digester volume per day; L is the volatile solids (VS) loading rate per day, θ is the Retention Time (RT), K is the kinetic parameter relating to the performance of the digester and μ_m is the maximum specific growth rate of the micro-organism (Chen 1983). B_o is the maximum theoretical methane yield (m³CH₄/VS_{kg}). The equation can be rearranged to give a methane yield per kg of VS added. This is more useful when the digester size is not known:

$$B = B_o \left(1 - \frac{K}{\mu_m \theta - 1 + K} \right), \text{ where } B \text{ is the methane yield m}^3\text{CH}_4/\text{VS}_{\text{kg}}. \quad 7-6$$

The methane yield per kg of VS intake (m³CH₄/VS_{kg}) is affected by the reaction time, the temperature inside the reactor, the ultimate methane yield and an inhibiting factor (called the kinetic parameter). The ultimate methane yield (B_o) is found to be independent of the operating temperature (Maly & Fadrus 1971) and for livestock waste it is dependant on feeding regimes and feedstuff quality which animals digest. According to Chen (1983) the B_o for pig manure can vary between 0.36 m³CH₄/VS_{kg} to 0.52 m³CH₄/VS_{kg}. This will have a significant impact on the overall methane yield of the digester.

The VS loading rate (L , with the unit VS_{kg/day}) is determined from the individual feedstock type and the rate at which the digester is loaded, whilst the kinetic parameter (k) is affected by the VS concentration. The maximum specific growth rate (μ_m) is dependant on the operating temperature which subsequently determines the retention time (θ). The equation calculates the actual methane generation from fermentation as opposed to biogas.

Although the model has been used for studying the methane production for all types of organic wastes (Chen 1983; Hill 1983; Karim et al. 2007; Lo et al. 1981), it has not been adopted when simulating co-digestion. When two or more organic waste types are mixed together, the concentration of VS and TS will subsequently be affected, therefore influencing the methane

yield. Through contact with an AD expert (P.Harris, University of Adelaide, 11/04/2008, personal communication) it was found that the VS and TS values cannot be directly added together to obtain the resulting values. Other studies also indicate the co-digestion of wastes cannot be modelled simply by adding the methane yields of separate digestion processes (Parawira et al. 2008). Research carried out on the co-digestion of potato waste and sugar beet showed that co-digestion could result in 60% higher methane yields per unit kg of VS digested (Parawira et al. 2008).

To summarise, theoretical models for estimating biogas yields cannot be used reliably. As a result of these findings and in accordance with other energy analysis studies of biogas (Berglund & Borjesson 2006), actual operating plant data was used rather than theoretical modelling of biogas yields.

The biogas (and energy) output from AD is significantly dependant on the material being digested. During a normal AD process, only around 50-90% of VS are destroyed (Figure 7-6) due to process inefficiencies. As these inefficiencies are extremely difficult to predict, theoretical modelling is not appropriate. When representing the biogas potential of the feedstock, it is common to show the methane yield from 100% decomposition of VS (Murphy & Power 2009; Ward et al. 2008).

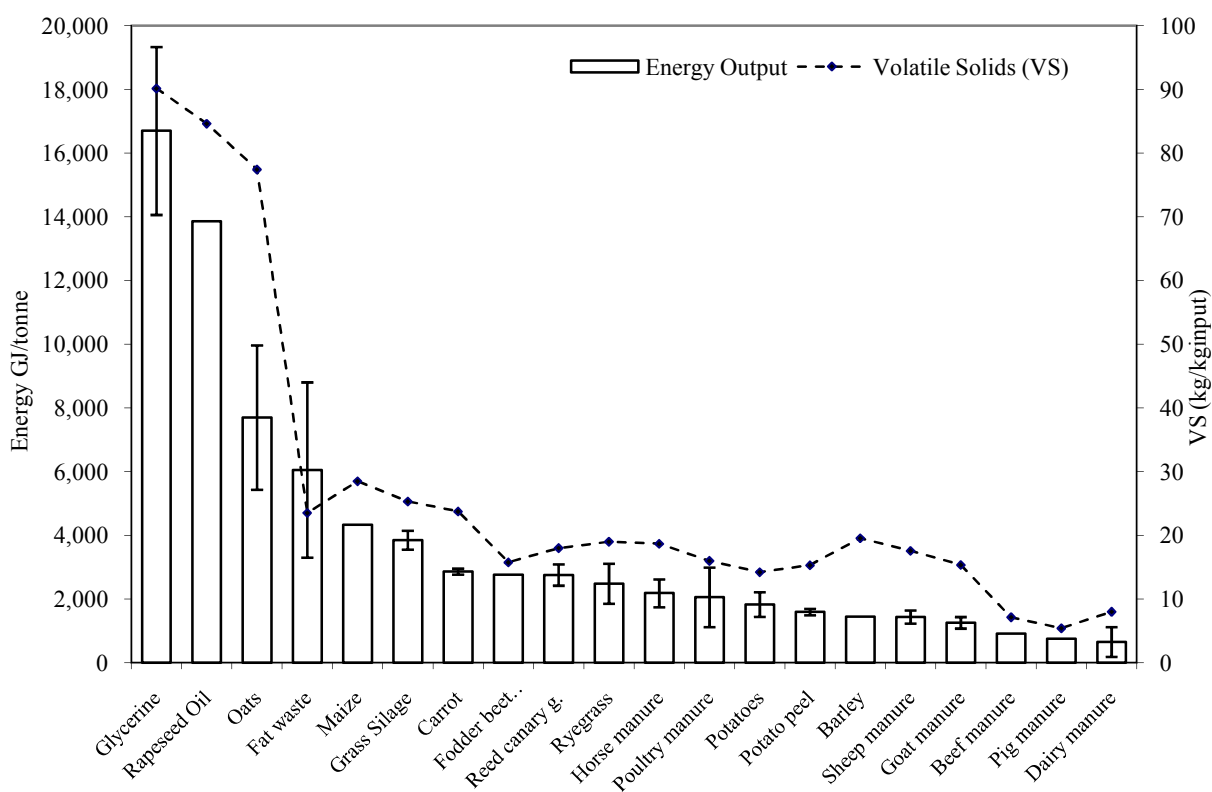


Figure 7-5 Energy content and volatile solids (VS) percentage per tonne of feedstock. Deublein & Steinhauser (2008); Ward et al. (2008)

From the literature review, it was found that materials such as fruits or vegetables were degraded relatively easily in an AD plant compared to manures, due to their low TS and high VS concentrations. Carbohydrate rich feedstocks were found to undergo a rapid hydrolysis stage leading to acidification and therefore inhibiting methane gas production (Gunaseelan 2004). Although animal manures registered at the lower end of the energy output, they are

currently the preferred primary feedstock for AD plants. This is due to their abundance and supplementary benefits of AD through waste management and odour control.

7.3.1 Biogas uses for energy systems

Biogas can be converted into three typical energy uses; thermal generation, electricity generation or use as a transport fuel. More recently, another available energy pathway has been to upgrade the biogas and inject it into the current national gas network. This requires large infrastructure and capital costs; around £100/MWh (National Grid 2009). To convert the biogas into any of these energy pathways, energy losses occur within the system.

The German AD plants analysed in this study operated using an internal combustion engine (ICE) setup consisting of a six-cylinder spark ignition or compression ignition engine, fitted with an appropriate power generator. Across the data range the electrical conversion efficiency ranged from 44% to 24% (FNR 2005). An average value of 34% was determined from a range of operating biogas plants. However, other studies indicated that the electrical efficiency of a biogas production plant would vary depending on the power rating. A study from Walla & Schneeberger (2008) showed that the electrical efficiency increased as the biogas plant size increased, through a study of plants between 25 kW to 2,500 kW. This correlation could not be seen when analysing the dataset in this study (FNR 2005). The efficiency of electricity production varied significantly but not in relation to the overall power rating of the plant. It was concluded that a possible cause for this was the varying biogas quality (methane concentration) present when fed into the ICE.

Analysing the operating plants further showed that installations with combined heat and power (CHP) had a heat efficiency rating between 17% and 56% (FNR 2005). An average value of 39% was determined for heat production. This equated to an overall CHP efficiency of 73%.

7.4 Results

A number of stages within the life cycle of biogas production were found to affect the energy balance of AD. Although transportation and growing/collecting energy consumption was found to be a contributor to energy inputs for biogas production, it appeared to be less significant than on-site energy use within the plant process itself (Berglund & Borjesson 2006). Heat energy requirements were found to be the largest energy sink within the AD process and were heavily dependant on the quantity of input. On average, around 248MJ of heat energy was used per tonne of feedstock.

Electricity consumption was recorded to be approximately 43 MJ/tonne of feedstock. Converting this value to primary energy shows an equivalent energy requirement of 116MJ/tonne; based on an electrical conversion efficiency of 32.7% (Allen et al. 2008b). A preliminary analysis therefore suggests that on average, heat energy use contributes towards around 70% of the on-site energy requirements, whilst electrical energy requirement accounts for the remaining 30%.

The following section of results shows the energy analysis of biogas production from AD in more detail. Additionally, net-energy analyses of the three case studies are also presented thus enabling an energy performance comparison between different AD setups.

7.4.1 Energy output based on feedstock

An analysis of energy output against feedstock VS concentration was carried out on German AD plants (FNR 2005). This confirmed the similarities between the theoretical results shown in Figure 7-5 and the results obtained from AD plants in Germany, shown in Figure 7-6. The energy output per tonne of cattle slurry through a typical AD plant was found to be between 500 MJ/tonne to 1,500 MJ/tonne (Figure 7-6).

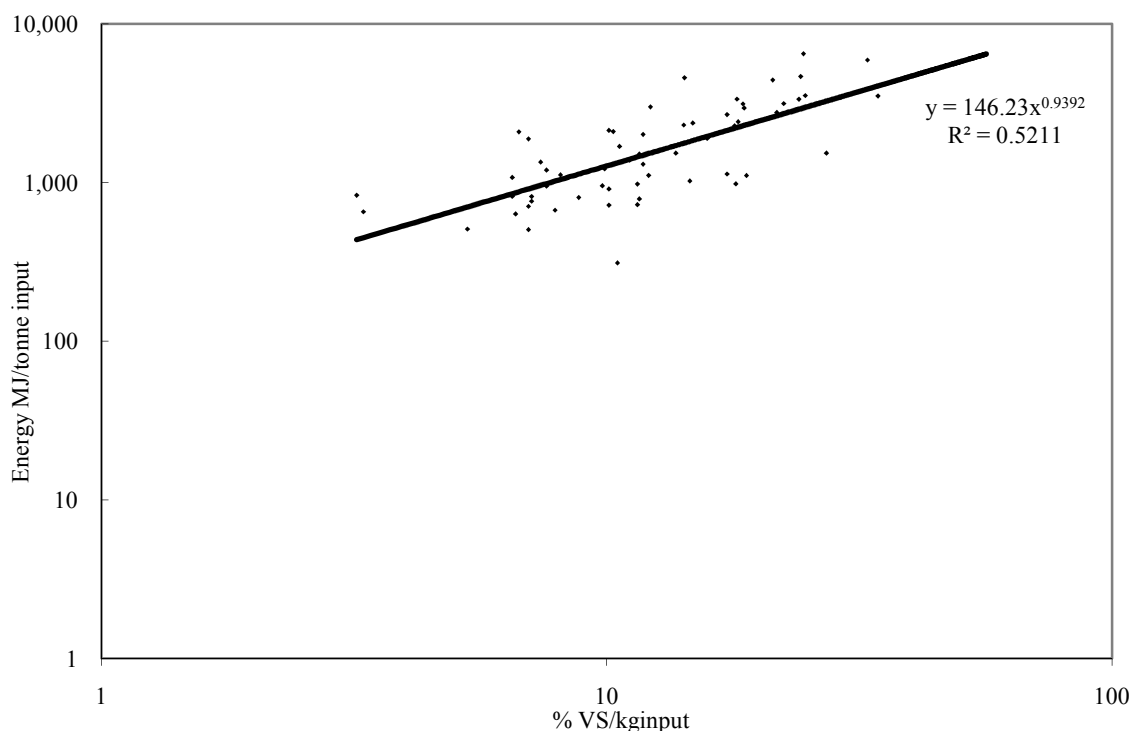


Figure 7-6 Energy output per unit input of feedstock vs. volatile solids percentage (VS %). Data from FNR (2005)

Figure 7-6 showed a clear link between the VS concentration and the energy released from digestion process. The results highlighted a strong regression (over 9/10) of energy output versus an increase in VS concentration per unit weight of feedstock used. This highlights the consistency with the theoretical results obtained from literature (Figure 7-5) and the results obtained from operating plants (Figure 7-6). The results highlight a surprisingly similar correlation, when considering the instability and sensitive nature of the AD system's parameters. Although there is a large standard deviation from the mean, it is apparent that the energy output of a plant is dependant on the VS concentration entering the plant.

The biogas output for the case study AD plant A was calculated to be 397 MJ/tonne of feedstock input. Even for single source dairy cattle manure feedstocks, this value was considered very low when compared to other existing operational plants. The low biogas output per tonne of feedstock would inevitably increase the energy requirement for energy (ERE), as a lower output is obtained per quantity of invested energy. The value of biogas output per unit tonne of input was found to be 17.1m³. Usually dairy cattle manure can produce over 25m³ (CH₄) of biogas per tonne of input (Ecofys 2005).

7.4.2 Embodied energy of AD plant construction

The AD plants investigated were generally of similar plant layout, equipment and construction material specification (FNR 2005). Therefore the construction embodied energy calculations shown in Table 7-1 were used as a basis for all AD plants. The total embodied energy of case study plant A was calculated to be 2,654 GJ_{NCV} (NCV denotes Net-Calorific Value). The calculated embodied energy of the plant was for a plant size of 250m³. Therefore a calculated embodied energy of 10.58GJ/m³ of plant size was obtained. This result was applied to the other operating AD plants for single-stage digester systems. This data was then compared to the total energy output of the plant assuming a 25-year lifetime.

The analysis showed that as the lifetime output of the plant decreased, the embodied energy of the plant construction contributed to a greater extent (Figure 7-7). In some cases, the embodied energy of the plant contributed up to 18% of the total energy output of the plant. This was a significant contribution as heat energy, electrical energy, feedstock production and transport energy were not taken into account for this part of the study. The results showed that if the biogas yield per tonne of feedstock material was high, then the impact of plant construction embodied energy was lower. On average, the results showed that embodied energy of plant construction contributed to around 10% of the total lifetime energy output.

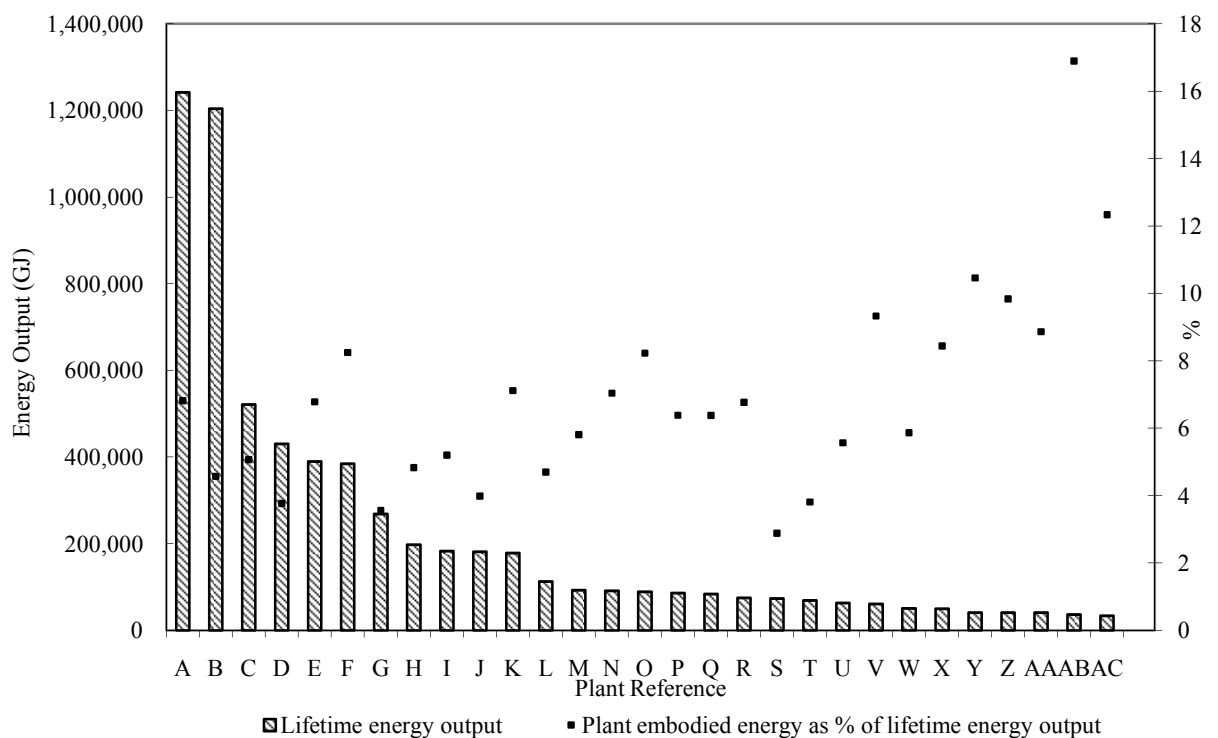


Figure 7-7 Lifetime energy output of single-stage AD plants vs. percentage contribution of plant construction embodied energy. Data adapted from FNR (2005)

7.4.3 Net energy of small-scale vs. large-scale AD systems

Having assessed the use of energy within AD plant construction, the following analysis compared the net-energy output between small-scale and large scale AD plants. Due to the variability of biogas yields depending on a feedstock type, a single feedstock was assumed, with a fixed biogas yield (25m^3 of biogas per tonne of feedstock inputted). This was a typical value common for manure (Ecofys 2005).

The analysis used typical single stage AD plants varying from 190 m^3 in digester size up to 8000 m^3 for a single digester. Using the results obtained for heat and electricity consumption from the previous sections, these two extremities were calculated. Analysing the ratio between AD plant energy requirements as a percentage of the plant's energy output (an alternative technique of representing the GER) showed that as the AD plant size increased, the ratio decreased. This signified that small-scale AD plants offered a lower energy output in relation to the GER invested within the system (Figure 7-8).

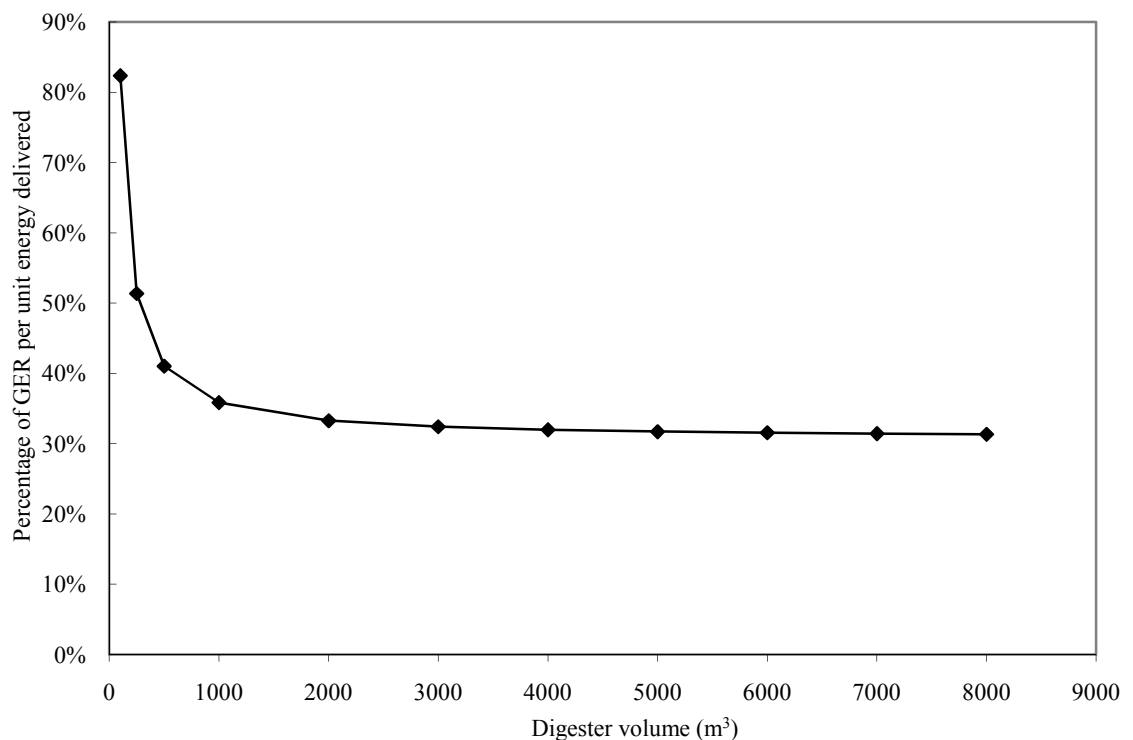


Figure 7-8 Percentage of GER against total delivered energy over life of AD

This finding showed a reduction in efficiency for digester sizes smaller than 500 m^3 , where up to and over 50% of the energy produced could represent the GER of the plant. The calculations assumed a methane quality of 60% in accordance with common literature (Twidell & Weir 2006).

The analysis confirmed that an increase in digester size would ultimately lead to a reduction in the use of energy resources and hence an increase in overall efficiency in terms of delivered energy (ERE). However due to the large number of operating parameters, care should be taken when interpreting these result. The analysis assumed that all plant sizes operated at the same digestion temperature and held the feedstock for a similar number of days. By varying these parameters, the input energy will vary as will the total output energy.

7.4.4 Life cycle energy analysis of case study plant A

The analysis was carried out for a small-scale AD plant situated in the UK (case study plant A), considered as a feasible option for the South West of England. The plant housed around 100 dairy cattle and waste was collected during the housing and milking period. Although the plant has been operating since 2002, there is no information available on the likely plant lifetime. Therefore, an assumption of 25 years was made. The biogas was used only for domestic thermal purposes and no electricity was made.

The plant digested around 653 m³ of cattle waste per year, with an average biogas yield of 17.1 m³/tonne of input. The biogas quality was reported to be between 58-64%; therefore, an average was chosen for the analysis. The energy use within the plant was divided into mechanical mixing, pumping energy and heating energy requirements. The embodied energy of plant construction was based on values from Table 7-1.

The reported electricity use per year was 2,806 kWh (10,101 MJ); this was equivalent to 30,892 MJ/year of primary energy, based on a conversion efficiency between primary and delivered energy of 32.7% (Allen et al. 2008b). The heat energy required for the plant had not been recorded; therefore an average of 244-250 MJ/tonne of feedstock was assumed as heat energy requirements (FNR 2005). An additional “start-up” energy input of 1,500 litres of kerosene was also used annually (J. Gascoigne, Greenfinch 05/05/2008, personal communication). This was effectively used as a process initiation. The heat energy requirement was converted to primary fossil-fuel energy use and resulted in a total of 830,000 MJ per year (SEDBUK 2009). This was similar to other results reported for small-scale AD plants (Berglund & Borjesson 2006). The annual energy consumption results have been tabulated in Table 7-5.

The plant was calculated to produce 5-6,000 GJ of methane (around 170,000 m³ of CH₄) over its life, with a total gross energy requirement (GER) of 50.9 MJ_{resource}/m³CH₄. The analysis showed the plant had a net-energy output of around -144 GJ per year (total net-energy of around -3,600 GJ over the plant lifetime). The plant was a net-energy sink rather than a source, thus producing less energy per unit of energy used within the plant. The delivered energy was used as a domestic heating/cooking gas. As a result the energy required to deliver this type of energy (ERE) was calculated to be 1.66 MJ_{resource}/MJ_{delivered}.

The typical cost of a small-scale AD plant (<400m³ digester) is reportedly around £750,000 in capital costs and further £190,000 in running and finance costs (Yeatman 2005). Given the costs of AD plant manufacture, it is questionable whether the net-energy gains can justify these plants as being financially feasible.

<u>Energy Output</u>		
AD plant biogas yield rate	17.1	m ³ /tonne
Annual feedstock input	653.2	tonnes/year
Annual biogas production	11,170	m ³ /year
Annual methane equivalent	7,149	m ³ /year
Annual energy output	255,921	MJ/year
Life cycle energy output from biogas	5,502,293	MJ
<i>Life cycle displaced energy from fertiliser (used for section 7.4.6)</i>	<i>2,662,000</i>	<i>MJ</i>
<u>Energy Input</u>		
Transport equivalent input	9,795	MJ/year
Primary heat energy input	244	MJ/tonne
Kerosene oil for start-up	227,506	MJ/year
Primary electricity input	30,892	MJ/year
Plant construction energy	2,654,925	MJ
GER of biogas	50.99	MJ_{resource}/m³CH₄
ERE biogas fuel	1.66	MJ_{resource}/MJ_{delivered}
Biogas life cycle net-energy	-3,613	GJ

Table 7-5 Energy analysis for case study AD plant A

7.4.5 Life cycle net energy analysis of case studies plant B and C

This study examined another two AD plants, both large-scale but with varying feedstocks (plants B and C). One plant (B) was used for electricity generation only, whilst plant C was used as a combined heat and power (CHP) plant. Plant B situated in the South West of England had a feedstock comprising of 57% farm slurry, 19% blood, 11% food waste, 8% chicken manure and 5 % other non-farm wastes (Cumby et al. 2005). The other plant (C) was fed with over 90% cattle manure and other crop wastes, but no food or non-farm wastes. The two plants were considered large-scale with B = 8000 m³ digester tanks and 277 m³/day input, and C = 2800 m³ digester tanks and 92.6 m³/day input.

The ERE was calculated for both plants based on energy inputs and outputs, in a similar manor to the small-scale AD plant (plant A). As shown in Table 7-6 the ERE for both plants is reduced when compared to the small-scale AD plant (plant A) in the previous analysis. This represented an improvement in net energy performance from that of plant A. Both plants B and C assumed a heat consumption calculated by the correlation found in Figure 7-2. The transport energy consumption was obtained from the literature for plant B (Cumby et al. 2005) and was correlated for plant C. The electricity consumption was also taken from plant operating literature (Cumby et al. 2005;FNR 2005).

	Plant B		Plant C	
<u>Energy Output</u>				
AD plant biogas yield	10,085	m ³ /day	3,077	m ³ /day
Methane equivalent yield	5,143	m ³ /day	1,723	m ³ /day
Biogas output energy output	184,132	MJ/day	61,688	MJ/day
Total annual AD plant energy output	67,208	GJ/year	22,516	GJ/year
Life cycle primary energy output	1,680,204	GJ_{primary}	562,900	GJ_{primary}
Life cycle delivered energy output	571,269	GJ_{delivered}	410,917	GJ_{delivered}
<i>Life cycle displaced energy from fertiliser (used in section 7.4.6)</i>	<i>Fertiliser cannot be sold</i>		137,150	GJ
<u>Energy Input</u>				
Heat primary energy input	60,944	MJ/day	21,970	MJ/day
Electricity primary energy input	10,998	MJ/day	1,019	MJ/day
Transport energy input	7,812	MJ/day	2,612	MJ/day
Co-substrate energy inputs	-	MJ/year	3,878,600	MJ/year
Total annual energy inputs	29,110,101	MJ/year	13,222,845	MJ/year
Plant construction energy	84,640,000	MJ	29,624,000	MJ
GER of biogas	17.7	GJ_{primary}/m³CH₄	22.9	GJ_{primary}/m³CH₄
ERE (delivered energy)	1.42	MJ_{resource}/MJ_{delivered}	0.88	MJ_{resource}/MJ_{delivered}
Biogas life cycle net-energy	-241,123	GJ	202,705	GJ

Table 7-6 Energy analysis of two large-scale plants (Plant B and Plant C)

The results show that plant B had a GER of around 17.7 MJ_{resource}/m³CH₄, whilst Plant C had a GER of 22.9 MJ_{resource}/m³CH₄. This highlighted that plant B was less energy resource intensive than plant C; however both of these larger scale plants used less than half the resources required for plant A per unit of biogas produced. Considering the delivered energy, plant B showed an ERE of 1.42 MJ_{resource}/MJ_{delivered}, whilst plant C 0.88 MJ_{resource}/MJ_{delivered}. Although the GER of plant B was lower than that of plant C, the delivered energy was only used for electricity production. This meant that plant B delivered less energy per unit of energy inputted than plant C. The latter plant used a CHP with a conversion efficiency of 73% (FNR 2005), whilst plant B was only able to deliver electrical energy as an output. Therefore plant C used the biogas more efficiently.

Plant B required fewer energy resources than plant C due to the latter requiring around 3,900 GJ per year of energy crops. Although maize silage contributed to less than 10% of the annual feedstock intake, 220ha of maize per year required around 18 GJ/ha of energy inputs (Martinez-Perez et al. 2007).

The dominant factor in the ERE calculations was the type of delivered energy provided by the system. The lack of heat re-use in plant B meant that it provided less delivered energy from the biogas consumed. Plant B was originally designed for CHP operation, but due to financial and technical issues, was never implemented. As a result, the biogas was used for electricity

generation only, reducing the actual delivered energy. The conversion efficiency of the electricity generation from both biogas plants was estimated to be around 34% in accordance with literature (FNR 2005).

Comparing the ERE of all three AD case studies showed that plant B performed marginally better than plant A, whilst plant C was the only plant to consume less energy than it delivered; thus showing an ERE less than one. Although plant A required a significant amount of energy resources, the use of the biogas amongst the case studies was the most efficient as it was converted directly to heat.

The GER of the three AD plants was found to be affected by the biogas yield efficiency of the materials digested. For plant B, this was around 36.4 m³/tonne of input, whilst for plant C, this was found to be 33.2 m³/tonne of input. These outputs were around double that found in the small-scale AD plant (17m³/tonne of input). Analysing the GER per methane unit produced, (as carried out by Slessor & Lewis (1979)) displayed that the GER of the plants appeared to be strongly affected by the biogas yield efficiency of the feedstock material. The scale of the plant also allowed the addition of high biogas yielding feedstocks such as food wastes and maize silage to boost the biogas output. As the small-scale AD plant operated solely on dairy cattle manure, the biogas output was more limited.

AD plant C was fed using 92% cattle manure. By undertaking a simple further analysis of the plant's total 92.6 m³ of feedstock; 85.1 m³ of manure would be required per day. Using a value of 9.6 m³/year/cattle of utilisable manure from dairy cattle (Soffe 2003), an estimate of the number of dairy cattle required to feed the digester was calculated. Assuming a 75% capacity factor; in line with typical AD plants (FNR 2005), the plant would require manure from approximately 2,500 dairy cattle.

In 2007, there were 652,216 dairy cattle in the South West of England (not including beef cattle (DEFRA 2007b)). If all dairy cattle waste were to be used in an AD plant such as plant C, the region could support around 260 AD plants of this scale. This could provide a significant amount of renewable energy to the region, simply from using cattle manure. This will be discussed further in the Chapter 10.

The overall energy analysis study acknowledged that a comparison of the ERE may have limitations and should be interpreted with care. This is because the delivered energy of these plants differed. The ERE can be used, as in this study, to yield comparative net-energy analysis results whilst not taking into account the type of delivered energy. The first law of thermodynamics does not differentiate between work and heat, thereby agreeing with this analysis in that there is no consideration of the quality of the delivered energy. The second law of thermodynamics however, differentiates between energy uses thus allocating a qualitative measure to the energy. In this case simply combining electricity and heat delivery together may show a misrepresentation of the ERE. The exergy (the measure of the delivered energy quality) would have to be considered in order to make the energy uses comparable. The GER, representing the biogas produced in this case, does not take into account the use of the delivered energy and as a result can be used as a representation of the energy resource requirements of AD plants.

7.4.6 Energy analysis including fertiliser as output

The analyses shown in the previous two sections examined the net-energy analyses based on the biogas output from AD only. This gave an understanding of the energy potential of a delivered bioenergy fuel such as biogas. Following the conventions of energy analysis the 'biogas' generator could also be credited with the amount of energy (in biogas equivalence) that it would have provided in total; thus including the natural fertiliser energy values of the digestate (Slessor & Lewis 1979). The study conducted by Slessor & Lewis (1979) calculated the displaced energy from adopting natural fertiliser from the digestate as a substitute for artificial fertiliser. Slessor & Lewis (1979) added the displaced energy from the fertiliser output to the biogas output, to obtain a total energy output of the plant. In this section, a similar approach has been undertaken; however there are a number of issues and clarifications which have to be addressed.

The production of biogas is used to deliver an energy fuel. The biogas can be used for any chosen delivered energy route. It could also be used as an energy source to manufacture artificial fertiliser. The digestate meanwhile, is a by-product of the AD plant. The digestate delivers a displacement of artificial fertiliser, rather than delivering a fuel. Additionally the fertiliser properties of the digestate would have been present even if the AD process were not undertaken. As a result the energy benefits (from displacement) of the digestate as a fertiliser were not combined with the delivered energy of the biogas in Table 7-5 and Table 7-6. This meant that the ERE of the plants did not take into account the displaced fertiliser energy potential.

The use of the digestate as a fertiliser however could displace the use of artificial fertilisers. Considering the embodied energy of fertilisers N, P_2O_5 and K_2O the typical energy consumed to manufacture a tonne of each type respectively was found to be 45 GJ, 18 GJ and 11 GJ (Nielsen et al. 2003). Nix (2009) reported that from 10 m³ (or 10 tonnes) of cattle farm yard manure (FYM), it was possible to recover 17 kg of N, 20 kg of P_2O_5 and 46 kg of K_2O .

Assuming these energy values for fertiliser production, the energy displaced by the by-product from AD has been shown in Table 7-5 and Table 7-6. For plant A, 653 m³ of FYM per year resulted in a fertiliser energy saving of just under 106 GJ per year. Calculated over the whole life of the plant, the energy saving would be 2,662 GJ. Similarly for Plant C, this was calculated to be 137,000 GJ. Plant B however, was not eligible to sell its by-product as a fertiliser due to the type of waste processed. As this was determined at the time of the site visit (May 2008), energy values could not be allocated to the digestate output.

Assessing multiple outputs from the AD process meant that the energy resource requirement (the GER) had to be allocated to the respective output of the AD plant. The outputs were considered to be either direct energy fuel as biogas or displaced energy from artificial fertilisers. For this, an energy allocation method was chosen in line with the methods highlighted in section 6.3.8. Using these allocation techniques the updated GER results have been shown in Table 7-7. According to a mass allocation, 40% of the inputs (GER) should be accounted for by the biogas production. According to an economic allocation only 12% of the inputs should be accounted for by the biogas production. The remainder of the GER inputs are allocated to the digestate fertiliser production

GER	Mass Allocation		Economic Allocation	
	Biogas (MJ _{resource} /m ³ CH ₄)	Fertiliser (MJ _{resource} /tonne)	Biogas (MJ _{resource} /m ³ CH ₄)	Fertiliser (MJ _{resource} /tonne)
Plant A	20.4	335.0	6.1	491.3
Plant B	17.7	-	17.7	-
Plant C	9.2	257.4	2.7	377.6

Table 7-7 Energy analysis of three case study AD plants (biogas & displaced fertiliser as outputs)

The table shows that as plant B did not produce any artificial fertiliser displacement, it could only allocate its GER towards biogas production. Whilst for plants A and C, if an economic allocation were used then plant A would show a lower GER for biogas production than plant B. As the energy content of a cubic metre of biogas is around 35.8MJ, the results shown in Table 7-7 signify that using both economic and mass allocation would result in less energy resources being required for biogas production than the energy potential of the gas.

The analysis has shown how the ERE can produce significantly different results compared to the GER as it is affected by the delivery of the energy. Therefore a recommendation is brought forward to use the GER to evaluate the operation of an AD plant in terms of energy resources for biogas production, whilst the ERE can be used to determine the most efficient way of delivering the energy irrespective of the medium.

7.5 Analysis of energy payback period

The next stage was to determine the energy payback period (EPP) of the AD plants. The EPP is defined as the time taken for the system to output enough energy to cancel out the energy invested in the system. In conventional renewable technologies such as wind turbines or solar PV, this is simply the amount of time taken for the output energy to equal the invested energy at the start of its life. However, as with all bioenergy systems, there is an annual operational energy expenditure which must also be taken into account. In this case, the payback is determined when the output energy equals the invested initial energy plus the operational energy consumption.

The time taken for an energy system to repay itself is also dependant on how the output energy is measured. If the energy outputs of a biogas plant are directly accounted for (electricity, CHP or heat delivered from the biogas), then the EPP considers delivered energy output only. If the total energy resource that the biogas displaces were considered, then a displaced energy payback period is calculated. This is because the biogas has the potential to displace existing (predominantly fossil-based) fuel sources.

The EPP can therefore take two forms: simple energy payback period and displaced energy payback period. Although the simple EPP represents a more graspable result, it does not show the holistic benefits or drawbacks of an alternative energy source. Additionally, by using a simple payback period, the three biogas plants could not be compared as their end-use energy pathways differ. For plant A, the displaced heat energy was from kerosene fuel, whilst the electricity generation from plant B and C displaced electricity from the National Grid. The CHP unit from plant C was assumed to displace natural gas heating.

The displaced electricity assumed a National Grid electricity conversion efficiency of 32.7% (Allen et al. 2008b). Plant A was used to displace a kerosene boiler with an average efficiency of 85%. Finally, the heat from the CHP plant was assumed to displace a standard natural gas boiler of 86% efficiency. Calculations showed that plant A would never be able to payback its energy investment, as either simple payback or displaced payback. However when also considering fertiliser output, the plant would pay itself back after 22 years, if displaced EPP were considered. Plant B had a payback period of just over a year when considering the fuels it was able to displace. Examining the simple EPP, plant B did not pay back over its lifetime. Finally, plant C which had an ERE of less than 1, had a simple EPP of 1.2 years and a displaced EPP of less than 1 year (shown in Table 7-8). This was lowered further when considering the fertiliser output.

<i>Biogas Output Only</i>	Plant A	Plant B	Plant C
ERE (MJ _{resource} /MJ _{delivered})	1.66	1.42	0.88
Simple delivered energy (MJ/year)	220,092	22,850,773	16,436,687
Energy resource saving/year (MJ/year)	258,931	69,880,038	29,734,360
Simple EPP	Never	Never	1.2 years
Displaced EPP	Never	1.3 years	0.4 years
<i>Biogas & Fertiliser Output</i>			
ERE (MJ _{resource} /MJ _{delivered})	1.01	1.42	0.66
Simple delivered energy (MJ/year)	326,572	22,850,773	21,922,687
Energy resource saving/year (MJ/year)	365,411	69,880,038	35,220,360
Simple EPP	Never	Never	0.01 years
Displaced EPP	22 years	1.3 years	0.4 years

Table 7-8 The energy payback period of three AD plant case studies

7.6 Summary

This chapter analysed biogas production with energy analysis techniques. The calculations compared the use of large-scale AD plants vs. small-scale AD and a variety of feedstocks. An understanding of how biogas output per unit input of feedstock affects the energy output was obtained. The most critical factor for an AD plant in terms of energy output is the biogas productivity of the feedstock. This result can vary considerably depending on the feedstock mixture. However, energy inputs through feedstock production and transportation were found to have a significant impact on the ERE of an AD plant. The ERE was also improved by around 20% if the fertiliser output is considered in terms of energy.

The energy analysis represented the energy performance of AD plants taking into account all types of outputs. Although the energetic properties of manure as a fertiliser were considered, these were not a result of the AD process. Therefore the energy analysis was represented with and without the energy benefits of fertiliser displacement.

These findings, along with LCA results and financial investment appraisal, are discussed in Chapter 10. The results are discussed and compared against a number of other renewable energy sources and in particular bioenergy production systems. Recommendations are also made on the optimum size and setup of AD processes which could be suitable for the South West of England.

8 LIFECYCLE ASSESSMENT OF BIOGAS

This chapter describes the findings from the lifecycle assessment (LCA) study carried out on an existing operational AD plant. The work followed the theory described in Chapter 5. The LCA studied an AD plant commissioned and owned by the Scottish Executive of the Environment and Rural Affairs (SEERAD) since 2003. The plant was designed as an AD facility with the aim of biogas production and improved manure management.

The aim of this study was to assess the environmental impacts associated with production of biogas for energy purposes. The feedstock, process layout and biogas use is the same for AD processes for energy purposes or pollution control. The overall system therefore did not differ and could be used to represent an energy production unit.

The plant denoted as plant A was suitable for the LCA study due to the extensive availability of operational data. Additionally, the plant was found to be one of the few in the UK to operate on a single source farm manure feedstock. Based on the findings from the energy analysis, it was highlighted that single source (or over 90%) feedstocks appeared to have the largest net available energy output. Therefore this plant was considered as a suitable model for the LCA study. Although the plant has been briefly explained and used in the previous analyses, a more detailed and comprehensive understanding of the plant has been carried out in this chapter.

8.1 *Motivation for study*

Studies of LCA for biogas production were found to be limited and incomplete within the literature (Berglund & Borjesson 2006; Ishikawa et al. 2006; Thyø & Wenzel 2007). Although there have been studies examining LCA of biogas, these did not appear to follow the methodology of standard LCA procedure (BSI 2006). LCA has also been more widely used for other bioenergy techniques, rather than biogas production individually (Guine & Heijungs 2007; Halleux et al. 2008; Nguyen & Gheewala 2008; Spirinckx & Ceuterick 1996).

The majority of published biogas analyses focused on energy and carbon balances (Berglund & Borjesson 2006; Chen et al. 1985; Ishikawa et al. 2006) as opposed to a holistic environmental appraisal. Studies which did focus on wider environmental impacts suggested that emissions from the AD process can vary significantly depending on feedstock utilisation and end-use of biogas (Borjesson & Berglund 2006). Other studies compared biogas against other transport fuels and showed that biogas from manure produced the largest reduction in greenhouse gas emissions (Thyø & Wenzel 2007). However, biogas from maize silage offered the largest greenhouse gas reductions for heat and power (*ibid*). A recent British study highlighted a detailed examination of the environmental impacts of a large-scale AD plant in UK (Cumby et al. 2005). However, the study did not examine the environmental impacts in-line with the relevant ISO standards for LCA making this study difficult to interpret and compare against other future LCAs. This was because the study did not define its system boundaries or follow the correct procedure highlighted in 6.3.1. Similarly, a number of the biogas LCA studies mentioned above have not clearly defined the study system boundaries.

As a result, it appeared that a detailed LCA study of UK biogas production had not been carried out. It was concluded that a holistic LCA of a UK biogas plant should be undertaken in

order to model the environmental implications of using this technology in the South West of England. The results could then be compared to previous findings, acknowledging the discrepancy between the study's system boundaries.

Limitations in data availability and the scarcity of operational data from other AD plants in the UK, gave reason for using this AD plant as a basis of study. The importance of using a single-source feedstock was also critical. Analysing the effects of other feedstocks would change the LCA results considerably. This would have meant that the LCA results were unique to a single AD plant only (with specific feedstock), rather than being used a representation of possible common AD setups. Therefore, the analysis was representative for the digestion of dairy cattle manure only, as this was the most abundant feedstock within the South West region and the most common feedstock used in current AD plants.

8.2 *Goal and scope*

The goal of this assessment was to examine and identify the life cycle environmental impacts of energy production from anaerobic digestion (AD). The objective was to identify the most important factors that affected the environmental load of a biogas generation plant. From these factors, the damages caused by the process were analysed, including the damages avoided from the displacement of a fossilised fuel.

By determining the environmental load of biogas production from AD, it was possible to identify whether the process had beneficial or detrimental affects on the environment. This was assessed using a number of environmental impact categories, including damage to human health, damage to ecosystems and the depletion of global resources. The assessment examined the production, delivery and the use of the biogas (cradle to grave). The by-product of the AD process (the digestate), used as a source of natural fertiliser, was also examined as a displacement of mineral-based fertilisers. Throughout the assessment, the production of the plant was accounted for and linked to the biogas and natural fertiliser outputs. The environmental impacts were assessed using EI99 LCIA methodology.

8.3 *Plant description*

The plant used for the assessment was based on a farm in the UK and was supplied with 100% dairy cattle waste from 130 dairy cattle. The waste was collected during the winter months and milking periods. The size of the plant was 250 m³ in digester size.

The AD setup comprised of a reception pit tank, 80 m³ in size, a single digester tank, a digestate tank (1012 m³) and biogas storage tank (5 m³). The feedstock was circulated around the plant using a combination of six centrifugal and positive displacement pumps. Other components within the AD plant included a macerator used for breaking down the particle size of the feedstock, a heat exchanger unit to heat the feedstock and a compressed gas re-circulation system. All feedstock and gas pumps were powered using individual three phase electric motors, controlled by a single control room situated near the heat exchanger unit. A schematic of the plant layout is shown in Figure 8-1.

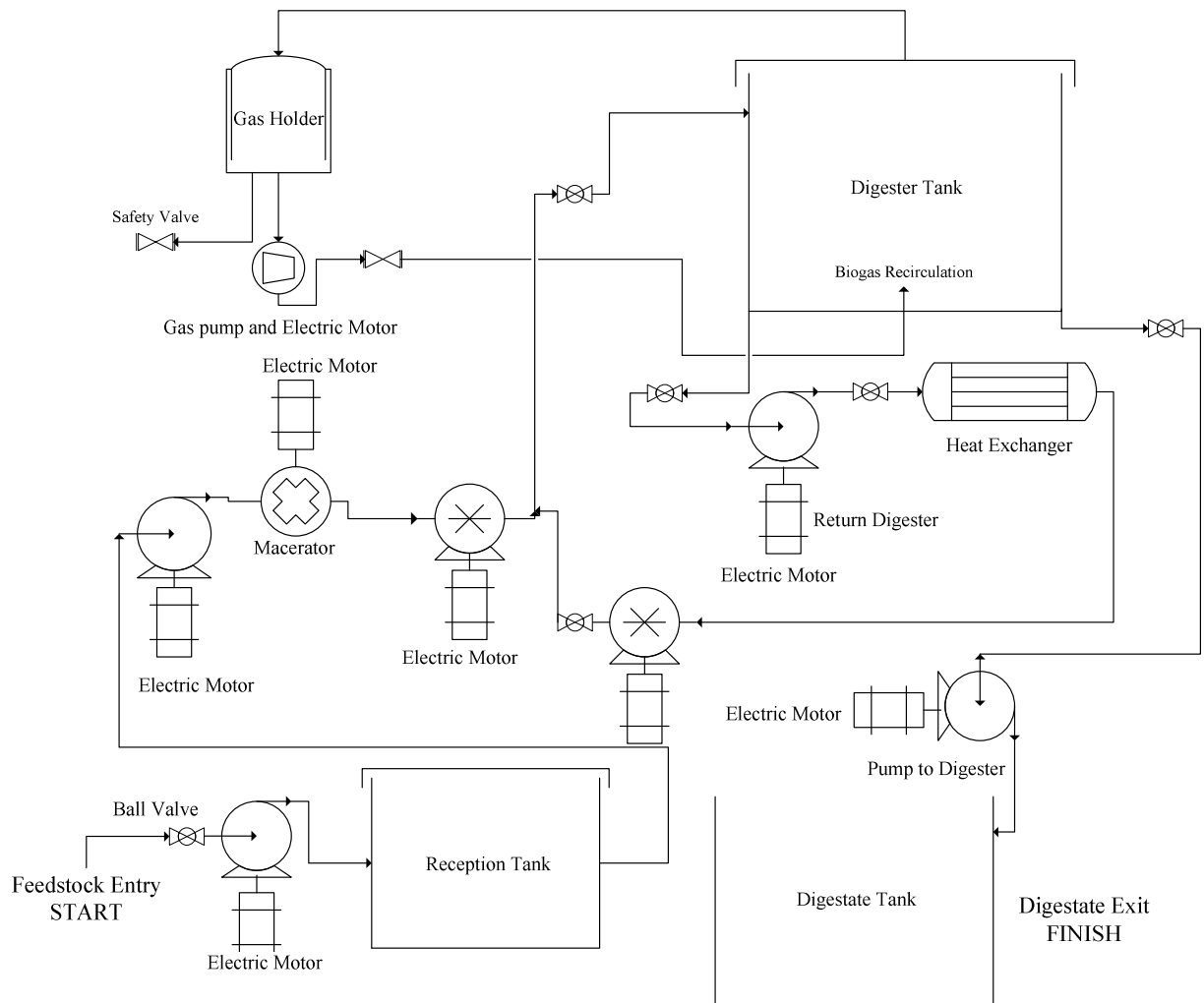


Figure 8-1 AD plant layout

The plant digested 653 m³ of dairy cattle waste (mixture of slurry and manure) per year. The plant retention time (RT) was 20 days and the biogas production was measured hourly. On average, around 8.89 m³ of biogas was produced per hour during the RT. The feedstock intake rate was 12.5 m³/day. The energy used within the plant was divided into two areas: heating of the digestate and electricity for pumping, mixing and shaping the feedstock. There was no direct water input into the digester; however water from the washing process of the milking parlour did enter the reception pit. The biogas was used primarily for heating the digester tank. However, the remaining biogas was delivered to the farmhouse situated on site, used for hot water, central heating and used within a Rayburn cooker. The AD plant was too small to produce significant biogas for electricity generation, as its feedstock supply was limited.

8.4 Functional unit

The functional unit of the analysis was a cubic metre of biogas. As the methane-quality was known, this was easily converted to an equivalent cubic metre of methane. The process of AD was described to be a multi-output process (see section 6.3.8). As a result, the second output (fertiliser) had a functional unit of mass (kilogram). This could be easily converted into a

biogas equivalent as it was calculated that one cubic metre of biogas produced 58.47 kg of natural fertiliser.

8.5 System boundaries of the study

The system boundary of the assessment is shown in Figure 8-2. The analysis system boundary commenced when the feedstock was collected from the cattle housing/milking parlour. The use of biogas was considered up to the point of use for heating energy. The boundaries did not consider the transport and spreading of the digestate as it was unclear as to how the digestate was distributed. Emissions associated with the AD plant construction were considered in terms of material use (mass) and some key manufacturing processes.

The biogas was understood to displace kerosene heating oil as a fuel. The fertiliser was considered up to production and substitution of artificial fertiliser. The effects of using the digestate as an artificial fertiliser were considered outside the scope of the study, as biogas for energy use was the primary focus. The study focused primarily on the biogas energy, rather than the by-product of AD process. The system boundary was the same as for the energy analysis, including the digestate as a potential artificial fertiliser replacement.

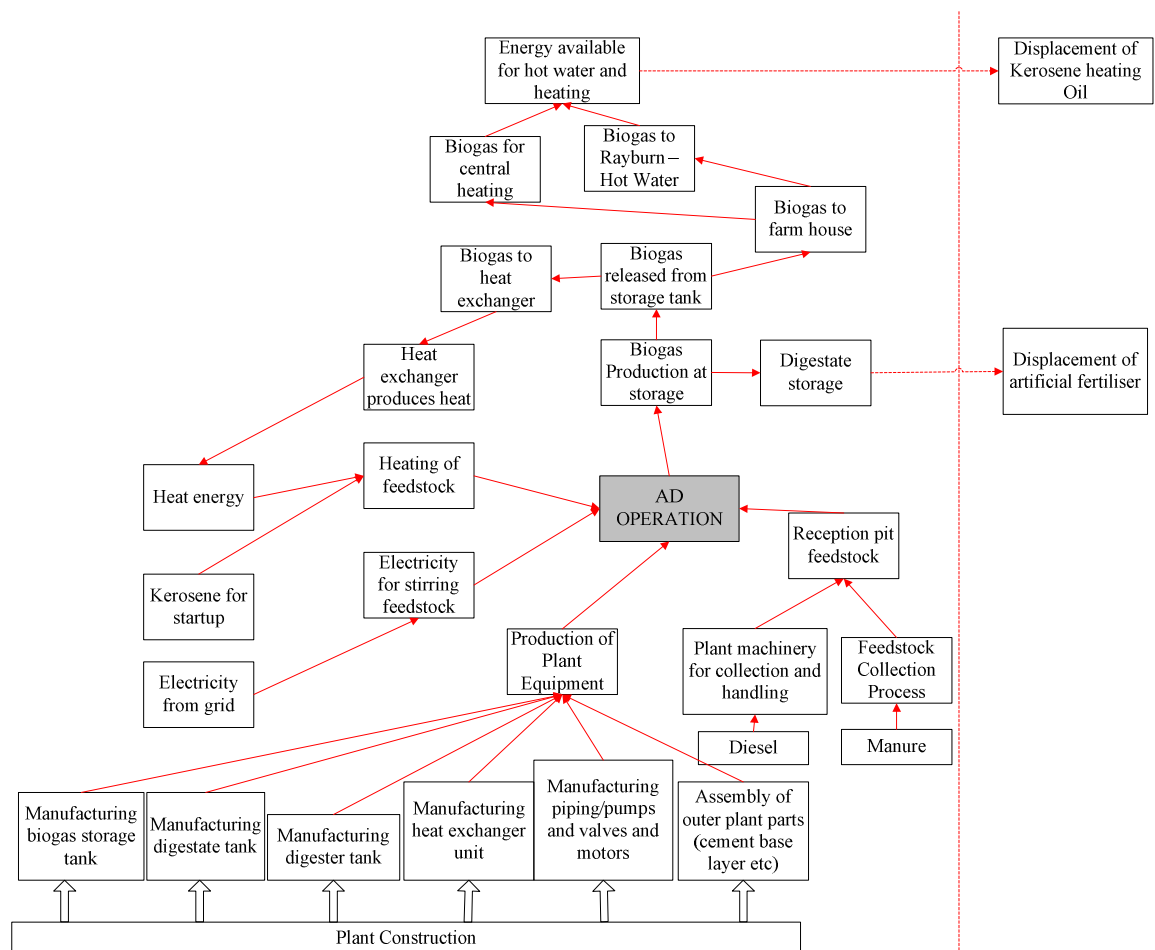


Figure 8-2 Lifecycle processes involved in biogas production from AD

8.6 *LCA of plant manufacture*

This section highlights the life cycle inventory LCI calculations and life cycle impact assessment (LCIA) results for the manufacture of the AD plant. The data was collected and analysed using SimaPro life cycle assessment software. The load towards the environmental impact categories was calculated using the Eco-Indicator 99 methodology. The following results are for the AD plant manufacture only.

The LCIA stage enabled the inventory analysis results to be interpreted in terms of environmental impacts according to societal preferences (Guinée 2002). The methodology assessed the damage of 11 impact categories. These results were then interpreted to determine the major contributors affecting the impact categories. In response to this, recommendations were made in order to reduce the damage from the impact categories.

8.6.1 Life cycle inventory data collection

An inventory of the plant assembly was generated, including major materials and the critical manufacturing processes. The material type and quantity was calculated based on findings from the manufacturer's website and site visits to the operational plant (Permastore 2009). The analysis also included special coatings and pre-treatment requirements required for the tanks. The plant manufacturing data and overall dimensions were obtained from the plant operator. A list of materials used within the plant construction is shown in Table 8-1. The list of plant components is also given in the Appendix B, with appropriate reference sources for each material.

<i>Plant Components</i>	<i>Assembly component</i>	<i>Weight/size</i>	<i>Material</i>
Digester Tank	Wall	22,307	kg Steel
	Insulation	623	kg Polyurethane
	Cladding	1,797	kg Steel
	Nuts, Bolts and Other	184	kg Stainless Steel
	Base (for all feedstock tanks)	182	m3 Concrete
	Seals	25.6	kg Sealant
Digestate Tank	Wall	46,323	kg Steel
	Nuts, Bolts and Other	310	kg Stainless Steel
	Seals	42.8	kg Sealant
Reception Tank	Wall	8,379	kg Steel
	Nuts, Bolts and Other	83	kg Stainless Steel
	Seals	11.52	kg Sealant
Biogas Storage Tank	Lid Weight	0.194	m3 Concrete
	Outer Skin	80	kg Glass Reinforced Plastic (GRP)
	Base	0.75	m3 Concrete
Heat Exchanger Unit	External Slurry Pipe	555	kg Stainless Steel
	Slurry Pipe to Digester	472	kg Stainless Steel
	Internal Water Pipe	101	kg of Stainless Steel
	Insulation	40	m Lagging Insulation (Rockwool)
	Container	2,230	kg Steel
	Piping and Valves	214	kg Stainless Steel
Stirring Device Auxiliary Equipment	x7 Electric Motors	160	kg Cast Iron
		23	kg Copper
		23	kg Steel
	x3 Centrifugal Pumps	108	kg Cast Iron
	x2 Positive Displacement Pumps	41.6	kg Cast Iron
	X2 Other Pumps	21.3	kg Cast Iron
		0.3	kg Steel
		0.3	kg Steel
Electrical Control Unit	Main Body	9	kg Steel
	Plastic Components	6	kg Plastics
	Circuit Board	3	kg of Printed Wiring Board
	Wiring	2	kg Cables
Digester Pre-Heat	Kerosene Boiler	9	kg Aluminium
		0.06	kg Brass
		6	kg Stainless Steel
		1	kg Plastics
		10	kg Insulation (Rockwool)
		140	kg Steel
		4	kg Copper
		14	kg Aluminium
Digester heater	Biogas Boiler	0.09	kg Brass
		9	kg Stainless Steel
		2	kg Plastics
		15	kg Insulation (Rockwool)
		211	kg Steel
		6	kg Copper
		20	kg Stainless Steel
Other			

Table 8-1 Material weights and volumes for AD plant manufacture

The plant had seven three-phase electrical motors installed. The manufacturing of these motors was based on Mueller & Besant (1999), where data was obtained from a range of electric motor manufacturers. A similar methodology was adopted for interpreting the construction of centrifugal and positive displacement pumps. The primary construction material (cast iron) data was then identified within the EcoInvent database (Frischknecht et al. 2005) and entered in the SimaPro LCA software.

The AD plant tanks were manufactured from steel. The tank wall thickness was understood to be around 12mm, through communications with the plant operator and reviewing the plant manufacturer's website (J. Gascoigne, Greenfinch 05/05/2008 personal communication; Permastore 2009). The wall insulation material (polyurethane) within the digester covered the inner lining of the tank in order to minimise waste heat. The insulation wall thickness was assumed to be approximately 80mm in accordance with literature (Ecofys 2005). The digestate and reception pit tank did not require insulation materials as these tanks did not undergo the digestion process. The heat exchanger unit was housed within a container of similar size and layout as a standard shipping container. The heat exchanger itself was constructed using stainless steel piping with a rockwool lagging around the heat exchanger.

The land requirement of the plant was also considered part of the construction phase. The land use for the plant was measured to be approximately 700m². The original land type was 'farmed land' and it was transformed from farming land into industrial land. The use of the EcoInvent database allowed the input of land use type and the amount of land required (in square metres). This accounted for the possible environmental impacts of land transformation. The database was based around the CORINE land cover database created by the European Environment Agency (European Environment Agency 1999). The database assessed the land-use of 12 different EU member states incorporating information such as; state of individual environments, quality and abundance of water sources, land-cover structure and state of soil, quantities of toxic substances discharged into the environment and list of natural hazards. A detailed explanation of the CORINE datasets has been published by European Environment Agency (1999).

The manufacture of the plant was then compared to the functional unit (1 cubic metre of biogas). This enabled the impacts of the plant manufacture to be evenly distributed across the entire biogas output of the plant. Based on a known annual feedstock input, and assuming a plant life span of 25 years, this equated to 16,330 m³ (or tonnes) of feedstock used throughout the whole life of the plant. One cubic metre of biogas required 58.47 kg of waste as feedstock. Therefore, the emissions of the plant manufacture contributed to 3.58e-6 of plant, per metre cubed of biogas output. As the plant life span was not known, an estimation was used.

8.6.2 Environmental impacts of AD plant manufacture – characterised results

According to the EI99 methodology adopted, the results for the characterisation stage were obtained by multiplying the inventory quantity (measured in based S.I. units) by the damage factors obtained from the Eco-Indicator 99 methodology. Following this, the results were then grouped into their corresponding impact categories and the percentage contribution was obtained for each impact category. The results show the contribution of each sub-assembly towards each impact category (Figure 8-3).

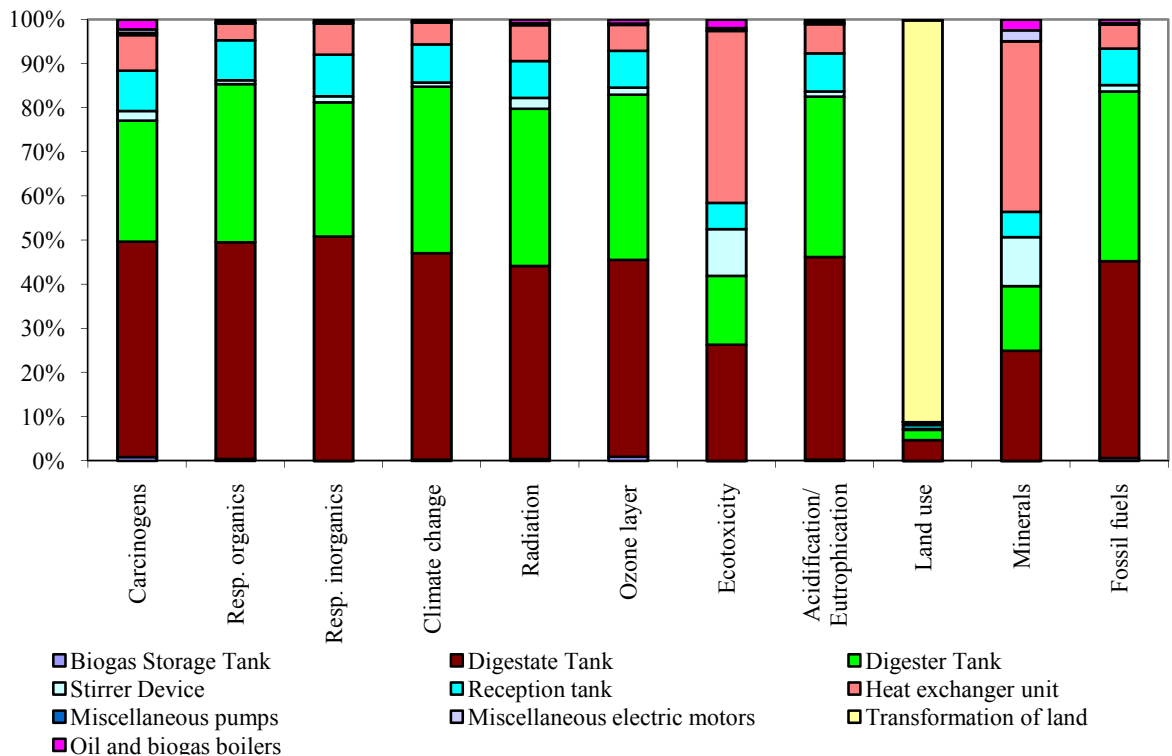


Figure 8-3 Characterised data for AD plant manufacture

The key findings of the characterised results were as follows:

- The largest contributors towards the impact categories were the digester and digestate tank manufacturing. These two tanks made a relatively large contribution towards impact categories: carcinogens, respiratory inorganics, respiratory organics, climate change, radiation, ozone layer depletion, ecotoxicity, acidification & eutrophication, minerals and fossil fuel resources.
- The reception tank was the third highest contributor (overall) towards the impact categories. As the construction materials for these three tanks were the same, this showed that a common material or manufacturing processes could be contributing towards the impact categories.
- The heat exchanger unit contributed towards all the impact categories, with a greater contribution towards ecotoxicity.
- Although 'miscellaneous pumps' and 'miscellaneous motors' represented 16 separate assemblies, the contribution towards the impact categories was insignificant.

The largest contributors to nearly all the impact categories were the largest sub-assemblies within the plant. Both of these assemblies had the highest material usage (a combined

consumption of over 60 tonnes of steel). The impact on carcinogenic effects was affected greatly by the steel use within the plant. This was due to the disposal of dust by-products from steel production. Other contributors to carcinogenic effects were due to the disposal of coal ash into landfill, which was used for electricity production. The emissions from iron ore extraction, used for steel production, affected the impact category of respiratory inorganics. This was due to the particulates emitted from the iron extraction process. Particulate matter can be generated by crushing, conveyance of crushed ore, blasting and transportation (Graedel & Howard-Grenville 2005).

Finally, the impact category 'land use' was mostly contributed to by the transformation of the land (around 700m²) into industrial land. The land was assumed to be converted from normal grazing land for cattle to industrial land. This caused damages to ecosystems, because of the change in land use. The unit for measuring the effects of land-use was the potential disappeared fraction of a species on land per year per square metre (PDF*m²yr).

8.6.3 Environmental impacts of AD plant manufacture – normalised results

Characterised data only represented the relative percentage contribution to each impact category. Therefore, at this stage it was not possible to determine which impact category was most significant, as the impact categories were all scaled to a percentage. The approach used by EI99 is to model the impact categories and compare the results against average emissions based in Europe. This stage converts the characterised data (DALY, PDF*m²yr and MJ) and normalised the data, thus making it dimensionless.

All the following graphs represented within this chapter will show the normalised data of varying parts for the biogas and fertiliser production. The graphs indicate a positive result (i.e. positive y axis) if there is a damage caused to the environment; whilst a negative result (negative of the y axis) shows a benefit towards the environment.

The results in Figure 8-4 show how the impact categories compared to the average emissions per inhabitant in Europe. Assessing the impact category of climate change, for example, showed that the manufacturing of the plant emitted four times more greenhouse gases than the average European inhabitant emits in one year. The highest impact category was found to be respiratory inorganics, followed by fossil fuel depletion, mineral depletion, land use change and climate change.

The most significant impacting categories (respiratory inorganics and fossil fuel resource depletion) were nearly three times greater when combined than the other impact categories. Respiratory inorganics, carcinogens, radiation, ozone layer depletion and acidification/eutrophication were considered to have minimal impact compared to the other categories.

Depletion in fossil fuel resources was found to occur through the use of heavy oils, natural gas and hard coal consumed for electricity production. These resources were also used for heat generation, for manufacturing of steel components and transportation requirements. These processes were considered necessary within the manufacturing of the AD plant. However, efficiency implementations, such as using recycled steel, reducing overall steel use, minimising transport distances etc. could reduce the impact on fossil fuel depletion.

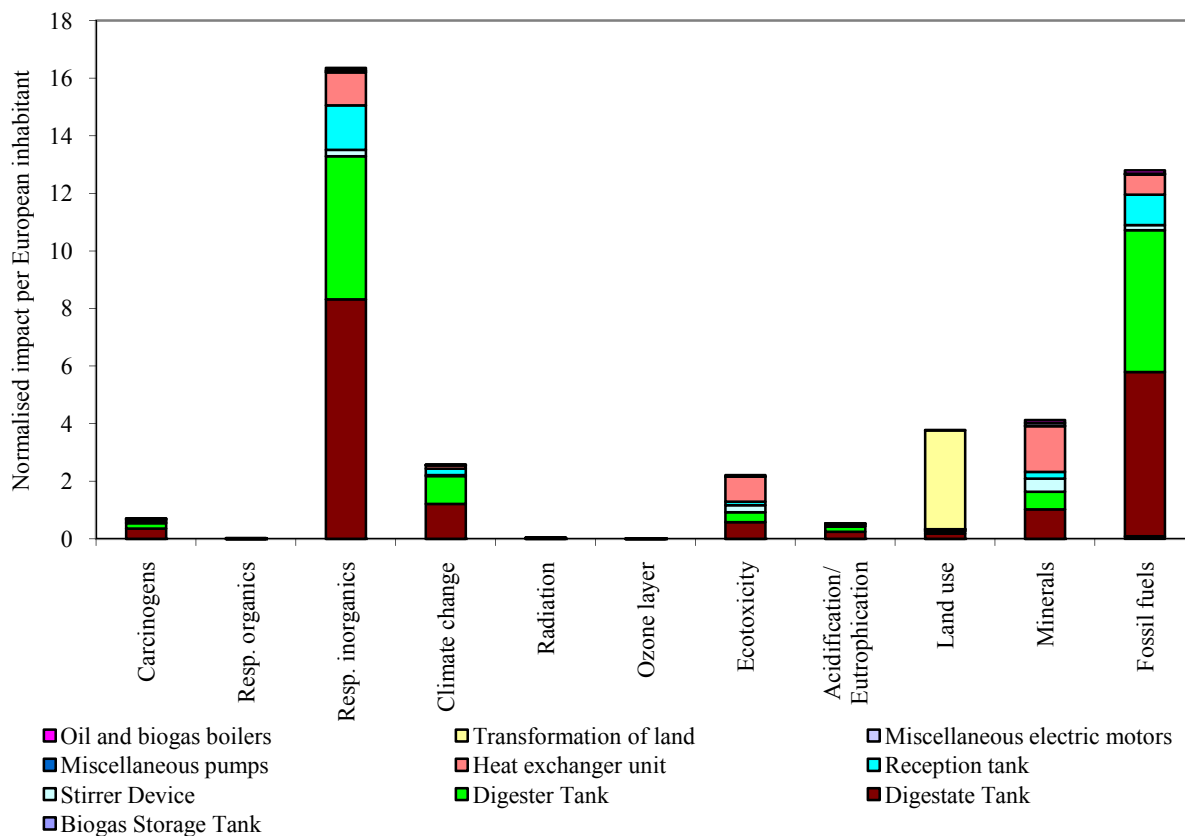


Figure 8-4 Normalised data for AD plant manufacture

The use of insulation material within the digester (polyurethane) was also found to have an impact on the depletion of fossil fuels. It was estimated that the plant used over 600 kg of polyurethane. If other materials were used such as cork or sheep's wool (organic materials), the fossil fuel consumption in the digester tank may have been reduced by over 70%. Polyurethane requires 85.2 MJ/kg of fossil fuels, whilst sheep wool and cork require around 20MJ/kg of material.

Damages to human respiratory systems can be caused through the emissions of a number of inorganic substances. In this study these were found to include particulate matter (PM), nitrate and sulphate, sulphur trioxide (SO₃), ozone (O₃), carbon monoxide (CO) and nitrous oxide (NO_x). These substances were found to cause chronic health effects and mortality. The majority of the contribution towards respiratory inorganics during the plant manufacture was due to the initial stages of steel manufacture. When obtaining iron ore, blasting techniques were used in order to separate the ore from the original source. The blasting created particulates of 2.5-10 µm in diameter. This particle size is sufficiently small to penetrate the human respiratory system and bring about serious health effects. Diesel combustion was also found to generate particulates, which may have lead to similar health effects.

Mineral resource depletion was mainly affected by the production of stainless steel (over 70% of the total impact). The composition of typical stainless steel (316-grade for example) is as follows: 16-19% chromium (Cr), 10-14% nickel (Ni), 2-3% molybdenum (Mo) and less than 2% other elements. The use of Ni, Mo and Cr are valuable mineral resources. As a result the depletion of these materials contributed significantly towards this impact category. Research carried out within the EI99 methodology showed that the resource depletion damage from

extracting Ni was 23 times greater (in terms of MJ surplus/kg) than that of Cr. Whilst Mo was twice that of Ni (Swiss Centre for Life Cycle Inventories 2007).

The plant used around 1,750 kg of stainless steel, primarily for heat exchanger pipes and circulatory piping around the plant. This piping was required to be durable and maintenance free; therefore, a high safety design factor was used when specifying the wall thickness of the piping. As a result, this impact could not feasibly be reduced.

8.7 Life cycle inventory and LCIA of AD plant use

This section highlights the life cycle inventory calculations and life cycle impact assessment results for the AD plant use-phase. The data was collected and analysed using SimaPro life cycle assessment software. The load towards the environmental impact categories was calculated using the Eco-Indicator 99 methodology. The following results are for the AD plant use phase only.

8.7.1 Life cycle inventory analysis

The direct inputs into the AD process were the feedstock material, the electricity use within the plant and the heat energy required to heat the feedstock. Other indirect inputs included the energy consumed in the farming machinery. This was treated as on-site feedstock handling energy requirements. Other indirect inputs included the water consumption used to wash the milking parlours and cattle housing. This was carried out primarily for hygiene purposes, although the addition of water to the feedstock was beneficial to the AD process. However, it was considered outside the system boundaries, as the AD process did not affect the quantity of water used.

Under normal operating conditions, the plant produced 8.89m³/hr of biogas. Of this, around 58-64% was methane (CH₄). Using an intake of 12.5m³ per day of feedstock and knowing that the total annual feedstock input was 653 tonnes, resulted in a plant operational time of 52.24 days per year (1,253 hours per year). The findings suggested that the capacity factor of the AD plant was as low as 14%. This meant that the impacts of the manufacturing stage were distributed over a lower output of biogas. This resulted in a higher environmental impact per unit output of biogas from the plant manufacture emissions.

The feedstock used was understood to be a mix of farmyard manure (FYM) and cattle slurry. A ratio of 55:45 was chosen, in accordance with other UK studies (Mistry & Misselbrook 2005; Williams et al. 2006). This was denoted as 'cattle waste' within this study. The Total Solids (TS) and Volatile Solids (VS) of the waste were 8% and 85% respectively. Using data obtained from the site visit, it was calculated that for every 12.5m³ of waste entering the plant; approximately 214m³ of biogas was produced over a 24-hour period. Therefore, the biogas production rate was 17.1m³_{biogas}/m³_{waste}.

8.7.1.1 Heat and electricity consumption

Although the power ratings were known for most of the electric motors, the plant had no recordings of individual equipment usage times. Despite this, results from the plant showed that around 2,806kWh of electricity were used annually. Based on 653 m³ of waste, a

calculated value of 4.29kWh/m³ of waste was used for total plant electricity consumption. This equated to around 0.29 kWh/m³ of biogas generated.

Heat energy required for the plant was derived from a mixture of burning some of the biogas produced and a small quantity of kerosene. The heat exchanger burner used around 11.5m³/hr of biogas during operation. However, this was 'as required'. As the maximum biogas yield was only 8.89m³/hr, the heat exchanger usage was maintained at a minimum. Data from similar German biogas plants were used to estimate the annual heat energy consumption, based on similar scales and feedstock (FNR 2005), as this data were not recorded for the plant studied. This was considered acceptable, as climatic conditions in Germany are roughly similar to those within the UK. The data showed a heat energy requirement of around 244 MJ/m³ of waste (14.5MJ/m³ of biogas).

The average annual domestic biogas energy demand was calculated to be around 3,200 m³, with a detailed calculation procedure shown in Appendix B. The remaining biogas was assumed to be allocated to the heating of the digester. The calculation steps suggested that the AD plant used around 273 MJ/m³ of waste.

8.7.1.2 Raw materials, diesel use in machinery, kerosene use and carbon balance

The feedstock collection point was situated less than 20-30 metres from the digester, therefore the transport distance was not predicted to have a significant impact. Nevertheless, diesel used by farm-machinery was considered. The machinery was estimated to consume 18 MJ/tonne of feedstock in accordance to similar research on biowaste AD plants (Spielman et al. 2007b).

The generation of animal waste was considered outside of the system boundaries, since the manure was a by-product of milk production. As a result, the use of manure for energy purposes produced a net consumption of CO₂ as a resource. This is known as carbon fixation where a value is given (kg or grams) to the amount of CO₂ used to make biogas. The carbon content of the organic matter was used to calculate the effective CO₂ savings. This value was generated from the composition of the waste, and is shown in Table 8-2. The data obtained to calculate this composition was actual data recorded from the plant and was supplied by the plant operator.

Cattle Waste Input (%)	100	
Dry Matter (%)	8	Source: (J.Gascoigne, Greenfinch 05/05/2008, personal communication)
Organic percentage of dry matter (%)	85	Source: (J.Gascoigne, Greenfinch 05/05/2008, personal communication)
Carbon content of organic matter (%)	58	Source: (Leeuwen & Vermeire 2007)

Table 8-2 Dairy cattle manure material properties

The carbon dioxide fixation per volume of cattle waste was calculated to be around 150kg/m³ of waste. In accordance to similar studies, this result was significantly low. Studies carried out for the EcoInvent database showed that CO₂ fixation for 1 m³ of biowaste was around 595kg.

This was due to the biowaste material's high dry matter concentration. As the dry matter for the FYM was much lower it was concluded that the value obtained was suitable for the analysis. Therefore, for this particular biogas plant, 150kg of CO₂ was required for biogas production for every tonne (or cubic metre) of waste processed. This value accounted for the carbon savings by using a biomass fuel as an energy source.

The study considered the feedstock for biogas production as a "free resource", implying all the inputs and emissions associated with the waste at the point of delivery were not included in the LCA. The impacts of making the feedstock (in this case a manure) should not be considered as these impacts would still occur if the feedstock was not used for biogas production.

Although the feedstock can be considered as a free resource, it has a carbon content which should be accounted for. When focusing on bioenergy forms the balance of the carbon is critical. One of the primary attractions for biomass use as a renewable energy source is its capability to create a balanced carbon cycle from production, extraction and use. For a correct representation of the carbon balance for biomass, the whole balance of carbon should be accounted for, signifying the carbon input must be equal to the output carbon. For this reason it is considered necessary to include the biogenic carbon potential of the waste.

This is necessary in order to achieve a neutral carbon balance whilst assessing the environmental impacts of bioenergy. If this approach were not used, biomass would be represented as a carbon emitting source, as carbon dioxide would be emitted during the combustion stage. The stored carbon within the biomass would therefore be accounted for in a similar way as the carbon emissions of fossil fuels; thus suggesting that biomass and fossil fuels have similar carbon emitting characteristics. An alternative to this could be to extend the system boundary to future plantation growth which would then recover the emitted carbon dioxide from the biogas combustion. Either way, the carbon within the biomass would ultimately be sequestered.

The AD plant required 1,500 litres of kerosene heating oil per year for the digester pre-heating start-up. As soon as a sufficient quantity of biogas was produced the kerosene boiler terminated, allowing the biogas boiler to operate and heat the feedstock. The net calorific value of kerosene for heating oil was found to be 34.8 MJ/litre (Esso 2004), equating to 52.2 GJ of kerosene use per year. The resource requirements for making one MJ of kerosene were obtained from the EcoInvent database where the production inputs and outputs were analysed. As the dataset was a European representative, it was deemed adequate for the analysis.

The combustion of one MJ of kerosene, which was not directly available from the EcoInvent database, was obtained and compared against a number of literature sources (IPCC 2006;Niels et al. 1997; Spielman et al. 2007a). Studying the literature displayed extensive reports of the emissions from kerosene combustion as aircraft fuel, whilst combustion from standard boiler use was more limited. A number of literature sources covering a wide range of kerosene combustion operations, were recorded and shown in Table 8-3.

	(Spielman et al. 2007a)	(Niels et al. 1997)	Light fuel oil burners*	Heavy oil burners*	(IPCC 2006)	Manufacturer (Grant ltd. 02/09/2009 personal communication)
	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ	g/MJ
CO ₂	72.2	157	74	77.9	71.5	75
CO	0.085	1.09	0.009	0.004	-	0.005
SO ₂	0.023	3.36	0.046	0.0468	-	-
NO _x	0.32	2.76	0.028	0.05	-	0.057
HC (VOC)	0.025	-	0.00029	0.00051	-	-
NM VOC	0.024	8.13	-	-	-	-
CH ₄	0.0011	1.78	0.0002	0.001	-	-
H ₂ O	28.4	402	-	-	-	-
N ₂ O	0.00069	0.0019	0.0007	0.0006	-	-

Table 8-3 Emissions from kerosene combustion from literature sources (*Swiss Centre for Life Cycle Inventories 2007)

The combustion of kerosene was found to be dependant on the composition and characteristics of the fuel. The sulphur dioxide emissions were directly linked to the sulphur content of the fuel (Spielman et al. 2007a). The way in which the fuel was combusted also affected the emission levels of carbon monoxide (CO), hydrocarbons (HC) and nitrogen oxide. Table 8-3 shows a range of emissions from kerosene combustion from a number of literature sources. The emissions varied significantly when compared against each other therefore, an average was taken from the literature sources.

The combustion of biogas was also considered in the study. The emissions of farm-scale AD combustion were studied extensively by Heck (2003) and reproduced by Spielman et al. (2007b). The data from these sources were compared to similar literature studies. Five datasets of emissions from biogas combustion were obtained and analysed (one of the datasets was for natural gas only, however as the key constituent of natural gas is methane, it was considered adequate for this study). The emissions varied depending on the conditions of combustion and the plant scale. Hydrogen sulphide emissions were found to be zero because it was converted to sulphur dioxide during combustion Cumby et al. (2005).

The dataset obtained from Cumby et al. (2005) represented biogas boiler emissions. However, the actual power of the boilers was unknown; therefore the emissions data could not be converted to unit energy output (MJ). This also applied to data obtained from landfill gas engine emissions (Environment Agency 2004). Although the landfill gas was assumed to have a similar composition to biogas, the emissions were calculated per cubic metre of exhaust gas, which could not easily be converted. An aggregation of the data obtained is shown in Table 8-4.

	(Cumby et al. 2005)	(Borjesson and Berglund 2006)	(Borjesson and Berglund 2007; Gustavsson 2002; Ishikawa et al. 2006)	(Borjesson & Berglund 2006; Edelmann et al. 2001)	(Spielman et al. 2007b)
SO ₂ (mg/MJ)	0.48 mg/s	2.9	0.3889	7.37	5.5
CO ₂ (kg/MJ)	3.9 kg/s	0.011	0.0580	0.017886	0.0187
NO _x (mg/MJ)	0.63 g/s	9.5	5.0	11.99	15.4
CO (mg/MJ)	1.26 g/s	7.6	-	29.92	35.2
CH ₄ (mg/MJ)	-	1.9	-	0.6116	17.6
HC (mg/MJ)	-	2.9	1.0	0.6116	2.2
PM (mg/MJ)	-	3.8	-	0	0.033
N ₂ O (mg/MJ)	-	-	-	-	1.1

Table 8-4 Emissions from biogas combustion from literature sources

8.7.1.3 Emissions to air and soil from AD outputs

The biogas produced did not undergo any cleaning or scrubbing processes to remove the hydrogen sulphide. As a result, these operations were not considered within the study. The study also assumed that no leakages occurred through pipes and seals. When digestate was stored in a post-digestion container, it maintained decomposition and released biogas at a lower rate. However, the analysis discovered it was financially unfeasible for the plant operator to extend the RT in order to capture the remaining available biogas. Therefore, the digestate emissions were released into the atmosphere through an open-top digestate tank. More advanced AD processes recapture the excess biogas through a second stage digestion process.

The analysis concluded that the feedstock was still digesting on entering the digestate tank. This was conceivable as the RT for the digester was amongst the lowest researched at just 20 days (commonly the RT is 30-40 days, if not longer). The Volatile Solids (VS) decomposition was approximately 70% within the digester, roughly in line with other similar European plants (FNR 2005; J. Gascoigne, Greenfinch 05/05/2008 personal communication). An analysis was carried out to determine the CH₄ and CO₂ yield from the post-digestion storage of the waste.

The analysis used the results obtained from a similar study using single source cattle manure as a feedstock (Spielman et al. 2007b). The source suggested that CO₂ and CH₄ emissions occurring from storage and handling (which would not have occurred for non-digested manure) were equivalent to 0.0212 kg/m³_{biogas} for CH₄ and 0.0759 kg/m³_{biogas} for CO₂, published by Spielman et al. (2007b) using data from Edelmann et al. (2001). The study from Edelmann et al. (2001) only considered the airborne emissions above those which would be naturally occurring from non-digestion of manure. Additionally, the study focused only on cattle manure feedstock, similar to the present study. As a result, these values were suitable for the LCA study.

The storage of digestate also releases other airborne emissions. These include carbon monoxide (CO), ammonia (NH₃), hydrogen sulphide (H₂S) (Deublein & Steinhauser 2008) and dinitrogen monoxide (N₂O) (Spielman et al. 2007b). The study analysed the following

emissions: NH_3 , N_2O and H_2S . The production of CO was found to be negligibly low (less than 0.2%) (Deublein & Steinhauser 2008) and therefore was not considered. According to Zicari (2003) H_2S emissions are combusted and converted into sulphur dioxide SO_2 . Therefore these emissions were only considered for the combustion stage of the biogas.

It was established that around 182g of N_2O was emitted per 10,260 kg of dairy cattle waste during animal storage (Williams et al. 2006). This equated to around 0.0177 g/kg (0.00104 $\text{kg}/\text{m}^3_{\text{biogas}}$) of cattle waste. Other sources showed that N_2O emissions were around 0.00105 $\text{kg}/\text{m}^3_{\text{biogas}}$ assuming a biogas quality of 60% (Borjesson & Berglund 2006). This value was considered accurate for use within the study as the plant setup was very similar. N_2O emissions from biowaste (a mixture of food and crop waste) digestion were reported to be around 5-6 times greater (Spielman et al. 2007b).

In large scale AD plants, the use of a nitrogen removal processes (commercially known as ANAStrip³) was found to eliminate nearly 100% of ammonia emissions. Ammonia in biogas was found to create damage to after burners but was also considered to have detrimental effects on the environment (Deublein & Steinhauser 2008). However due to the scale of the plant studied, no ammonia filter was used, consequently the emissions of ammonia were considered.

From UK studies of undigested dairy cattle waste, the recorded ammonia emissions per cubic metre of waste were around 0.61 kg/m^3 (Williams et al. 2006). However studies from European dairy cattle waste AD plants, reported an ammonia emissions increase from pre to post-digestion of around 8-9% (FNR 2005). This equated to an ammonia release of around 0.67 kg/m^3 of manure (0.039 $\text{kg}/\text{m}^3_{\text{biogas}}$). The results from Edelmann et al. (2001) showed that ammonia released from the storage and digestate handling was calculated to be 0.0102 $\text{kg}/\text{m}^3_{\text{biogas}}$ for cattle manure. The study adopted an average of these results (around 0.025 $\text{kg}/\text{m}^3_{\text{biogas}}$) and a sensitivity analysis was carried out using both extremities. The overall emissions to air from the digestion of cattle waste are shown in Table 8-5.

Emissions to Air	Unit	Amount
CH_4 Methane	$\text{kg}/\text{m}^3_{\text{biogas}}$	0.0212
CO_2 Carbon dioxide	$\text{kg}/\text{m}^3_{\text{biogas}}$	0.0759
N_2O Dinitrogen monoxide	$\text{kg}/\text{m}^3_{\text{biogas}}$	0.0012
NH_3 Ammonia	$\text{kg}/\text{m}^3_{\text{biogas}}$	0.0249
CO Carbon monoxide	-	Trace

Table 8-5 Emissions to air from digestate handling

The emissions to soils were obtained from the composition of the cattle waste pre and post-digestion. Quantities for calcium (Ca), magnesium (Mg), sodium (Na), zinc (Zn), copper (Cu), iron (Fe), manganese (Mn), aluminium (Al) and sulphur (S) were obtained from the Scottish Agricultural College (SAC). These were recordings taken during a digestate sampling at the plant and have been shown in the Appendix B. Other heavy metals found to be present in cattle manure, included: phosphorus (P), cadmium (Cd), chromium (Cr), nickel (Ni), lead (Pb)

³ ANAStrip is a process that re-circulates the gas into a high temperature, low-pressure stripper leaving the gas ammonia-enriched. The gas is then passed through a scrubber where the ammonia reacts with an absorbent in water to create ammonium sulphate, which can be used as fertiliser.

and potassium (K). This data was obtained from various literature sources (Pinamonti et al. 1997; Sweeten et al. 1986; Van Horn et al. 1994). The total emissions to soil are shown in Table 8-6.

The study found that although this chemical composition was present within the digestate and could possibly have an impact on environmental emissions, these chemicals were not produced as a result of the AD process. Studies from Pinamonti et al. (1997) and Williams et al. (2006) only showed the chemical compositions from undigested cattle manure as opposed to digested manure. As a result, these values could not be used when creating the LCI. The real emissions from AD were therefore from the difference between undigested and digested feedstock.

Emissions to Soil	Digestate Value	Δ Digestate vs. intake	Unit
Phosphorus ^a	0.040	0.00003	kg/m ³ _{biogas}
Cadmium ^b	3.274E-06	-	kg/m ³ _{biogas}
Chromium ^b	0.0002	-	kg/m ³ _{biogas}
Copper ^a	0.0008	0.0001	kg/m ³ _{biogas}
Nickel ^b	5.613E-05	-	kg/m ³ _{biogas}
Lead ^b	0.0001	-	kg/m ³ _{biogas}
Zinc ^a	0.0007	0.0002	kg/m ³ _{biogas}
Iron ^a	0.011	0.002	kg/m ³ _{biogas}
Calcium ^b	0.341	0.0299	kg/m ³ _{biogas}
Potassium ^b	0.035	-	kg/m ³ _{biogas}
Magnesium ^a	0.114	0.008	kg/m ³ _{biogas}
Sodium ^a	0.049	0.007	kg/m ³ _{biogas}
Manganese ^a	0.002	0.0002	kg/m ³ _{biogas}
Aluminium ^a	0.004	0.0009	kg/m ³ _{biogas}
Sulphur ^a	0.023	0.003	kg/m ³ _{biogas}

Table 8-6 Emissions to soil from digestate. Source (a) denotes data from the SAC, whilst (b) is data obtained from Pinamonti et al. (1997), Sweeten et al. (1986), Van Horn et al. (1994)

Research carried out by the Scottish Agricultural College (SAC) examined the entry feedstock composition and the effluent composition of manure as a feedstock. The study found that there was a slight increase in all of the chemicals examined, however this change was very small. These were considered the actual contributors towards the LCI of the digestate. The results in Table 8-6 are recorded data of the actual plant used for this study.

The digestate from the plant was assumed to displace artificial/inorganic fertilisers. Inorganic fertilisers are available in a range of forms with varying compositions of 'active ingredient', which are N, K₂O and P₂O₅ (Nix 2009). These were found to be the key elements in the digested manure making it suitable for fertiliser use. The outputs of these nutrients from the AD digestate were obtained from data published in ADAS (2007). This report published actual nutrient values of the AD plant for this study. The values in Table 8-7 show the nutrient composition of the digestate along with the potential inorganic fertilisers that the digestate could displace. The analysis carried out on the AD plant showed that N nutrients remained the same, whilst P₂O₅ and K₂O nutrient values decreased by 2.5% and 2% respectively.

The digestate nutrients were understood to be capable of displacing three typical inorganic fertilisers. The three inorganic fertilisers, which the digestate could displace, were ammonium nitrate (N), triple superphosphate (P_2O_5) and potassium chloride (K_2O). These inorganic fertilisers were chosen based on the similarities to the digestate properties (Nix 2009;Soffe 2003).

The analysis found that a cubic metre of digestate could contribute approximately 18 kg of inorganic fertiliser substitution, if muriate potash, triple superphosphate and ammonium nitrate were to be displaced. The LCI data for these three inorganic fertilisers were reviewed and obtained from the EcoInvent database (Nemecek & Kagi 2007). These inventories were representative for European scenarios and incorporated the same concentration of active ingredient as shown in Table 8-7 (Nix 2009; Soffe 2003).

Nutrient properties	Input (feedstock)	Output (digestate)
N Fertiliser (kg/m ³)	2.9	2.9
P_2O_5 (kg/m ³)	1.11	1.08
K_2O (kg/m ³)	4.3	4.2
Inorganic fertiliser displacement	Concentration	1m ³ digestate is equivalent to
Ammonium Nitrate	35% N conc.	8.29 kg
Triple Superphosphate	47% P_2O_5 conc.	2.3 kg
Muriate of Potash (Potassium Chloride)	60% K_2O conc.	7.2 kg

Table 8-7 Nutrient composition of digestate

8.7.2 Environmental impacts of AD plant use phase – biogas and fertiliser production

The next stage determined the impact categories affected by the use-phase of the AD plant. It then compared these results to the environmental impacts caused by the plant manufacture. The impacts from the plant manufacture were scaled to the equivalent of a single unit of biogas output (one cubic metre). It was calculated that the emissions from a single cubic metre of biogas were equivalent to the emissions from 3.58e-6 parts of the plant (meaning that over the plant's entire life it produced 279,329m³ of biogas and one cubic metre of biogas effectively required 3.58e-6 parts of the plant).

As there were two outputs of the AD plant, it was necessary to adopt the allocation results obtained in section 6.3.8. The results showed that according to an economic allocation, 12% of the impact category results were allocated towards the biogas production. Following a mass allocation, 40% of the impact category results were allocated towards the biogas production. The results also displayed the environmental impact categories with no allocation meaning all the environmental effects were a result of the biogas production; thus ignoring (momentarily) the fertiliser production. This was used simply as a comparative reference point.

Figure 8-5 shows the allocated and unallocated normalised impact category results, compared against the impact category results of the plant manufacture. The allocation methodology was found to have a very large effect on the scale of the environmental impacts for biogas

production. For some impact categories such as respiratory inorganics, the difference in allocation percentage had a significant effect on the damage towards that impact category.

The most significant environmental impact from the normalised results was the effect on respiratory inorganic from biogas production. Over 70% of the total impact was contributed by the biogas production and the remaining 29% affected by the plant manufacture. The emissions contributing towards respiratory inorganics were primarily found to be a result of the air emissions from the digestate storage. Other emissions from kerosene combustion at start-up, diesel and biogas combustion for digester heating, also contributed to this impact category. Emissions such as particulates and sulphur dioxide contributed towards the high impact on respiratory inorganics.

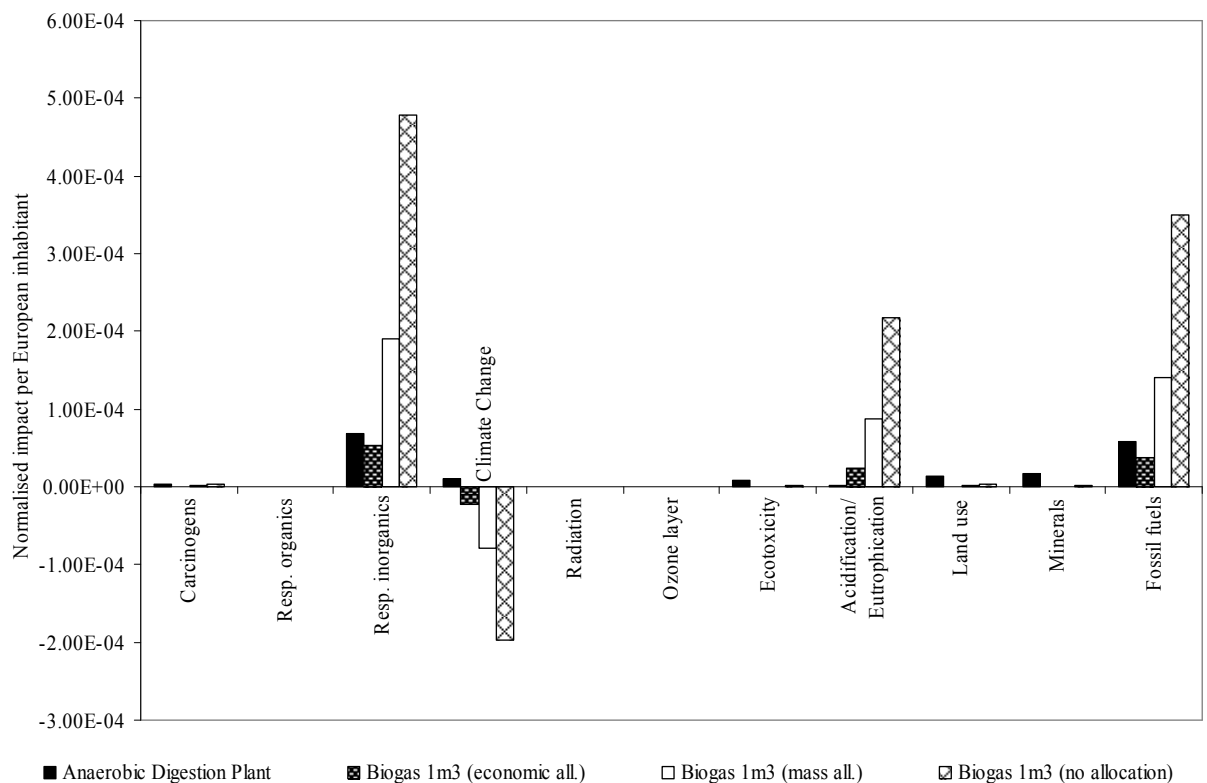


Figure 8-5 Normalised data of biogas production vs. AD plant manufacture (positive results indicates a damage to the environment whilst a negative result indicates a benefit)

The production of biogas showed a negative effect on the impact category of climate change. This was due to the potential carbon dioxide emissions sequestered from the organic matter. The CO₂ fixation was accounted for as a consumption of the CO₂ resource. This theory assumed that carbon dioxide was consumed to generate the feedstock (animal feedstock production) and therefore was required within the plant. The CO₂ is stored within the biogas in the form of CH₄ (and some CO₂) until the biogas is combusted.

Other areas in which the production of biogas contributed significantly towards the environment, was through the detrimental affect on fossil fuel reserves. This was due to the depletion of kerosene and diesel fuel. EI99 methodology values the reserves of oil more highly than the reserves of coal, based on the energy required for extraction. This may be seen through the current market prices of oil and coal where oil is valued at around 3.3p/kWh whilst coal is valued at 1.1p/kWh (DECC 2008). However these may be more affected by

market demand rather than resource availability. Therefore, the use of kerosene and diesel fuel throughout the process contributed significantly to the impact category of fossil fuels. In addition to this, the biogas used to heat the digester was relatively high compared to similar AD plants for other literature sources (Spielman et al. 2007b). As a result, the plant efficiency was lower.

The end-user demand for biogas (the farmhouse, in this study) was found to be smaller than the available biogas. Excess biogas would therefore be used to heat the digester further (on occasions it was reported to run at 42°C rather than 37°C). Although the biogas was considered a free resource, the LCA accounted for all the resources required to make the biogas in the first instance (i.e. kerosene, electricity etc). It was apparent that the excess biogas burnt on the digester was detrimental to the environment. The plant could be modified to house a larger quantity of biogas rather than the current five cubic metres. This would then reduce the need to 'flare' excess biogas.

Emissions such as ammonia, nitrogen dioxides and sulphur dioxides contributed towards the impact categories acidification and eutrophication. The combustion of kerosene, diesel and biogas emitted nitrogen oxides and sulphur dioxide, whilst ammonia was generated during the digestate storage stage. Emissions contributed by biogas could be reduced significantly within the plant if appropriate measures were put in place. Nitrogen oxides and carbon monoxides could be converted into oxygen, carbon dioxide and nitrogen if the biogas boiler were fitted with a catalyst converter. Sulphur dioxide could be reduced by removing the hydrogen sulphide through a desulphurisation process within the plant (Ecofys 2005).

Figure 8-6 shows how the impact categories were allocated to the production of a natural fertiliser (denoted as the digestate). The results were similar to those of the biogas production for each impact category. However, the digestate was calculated to have a much greater allocation of impacts for both methods (mass or economic).

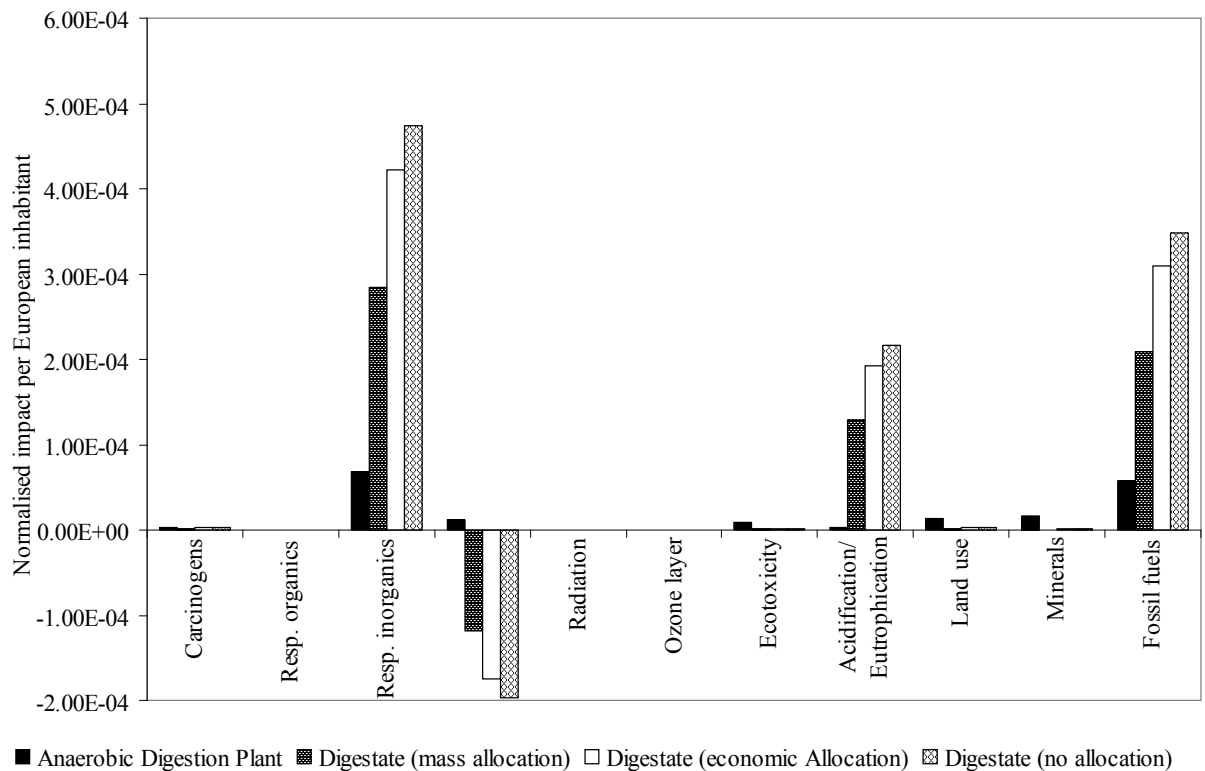


Figure 8-6 Normalised data for digestate production vs. AD plant manufacture

The environmental impact contributions of the digestate were compared against the contribution from the plant manufacture and the two different allocation methods. The economic allocation method calculated the digestate to be responsible for 88% of the emissions from the plant, whilst the mass allocation contributed 60%. The representation of 'no allocation' is used for relative comparison towards the allocated results.

8.8 AD outputs as a displacement for kerosene fuel and inorganic fertilisers

The following section describes the environmental impact life cycle assessment results of using the AD outputs as a displacement of kerosene fuel and inorganic fertilizer. The results show the impact of producing the AD outputs compared with the impacts from avoidance of kerosene and fertiliser production.

8.8.1 Environmental impacts of displacing kerosene

The analysis examined the impacts created and avoided for the biogas used as displacement of kerosene. Kerosene was chosen as this was the conventional fuel source used on-farm for heating purposes. The first stage of the results showed the normalised data of the production of biogas compared to the production of kerosene (Figure 8-7). The production of kerosene was based on data collected and stored in the EcoInvent database, representative of kerosene production in Europe. In order to displace 1 kg of kerosene, 1.795 m³ of biogas was required. The analysis shown in Figure 8-7 represents the displacement results. These values were calculated by determining the impacts from the biogas production emissions and subtracting the impacts from the displaced kerosene production.

The production of biogas had a positive effect on reducing the impact category for fossil fuel resource depletion and climate change. This was because the displacement of kerosene signified a reduced requirement for fossil fuels. Although the biogas production consumed a small amount of kerosene, this caused a significantly lower impact on fossil fuel resource depletion in comparison to using kerosene solely as a fuel. The carbon dioxide savings from biogas production were also indicative of the reduction on the effects of climate change.

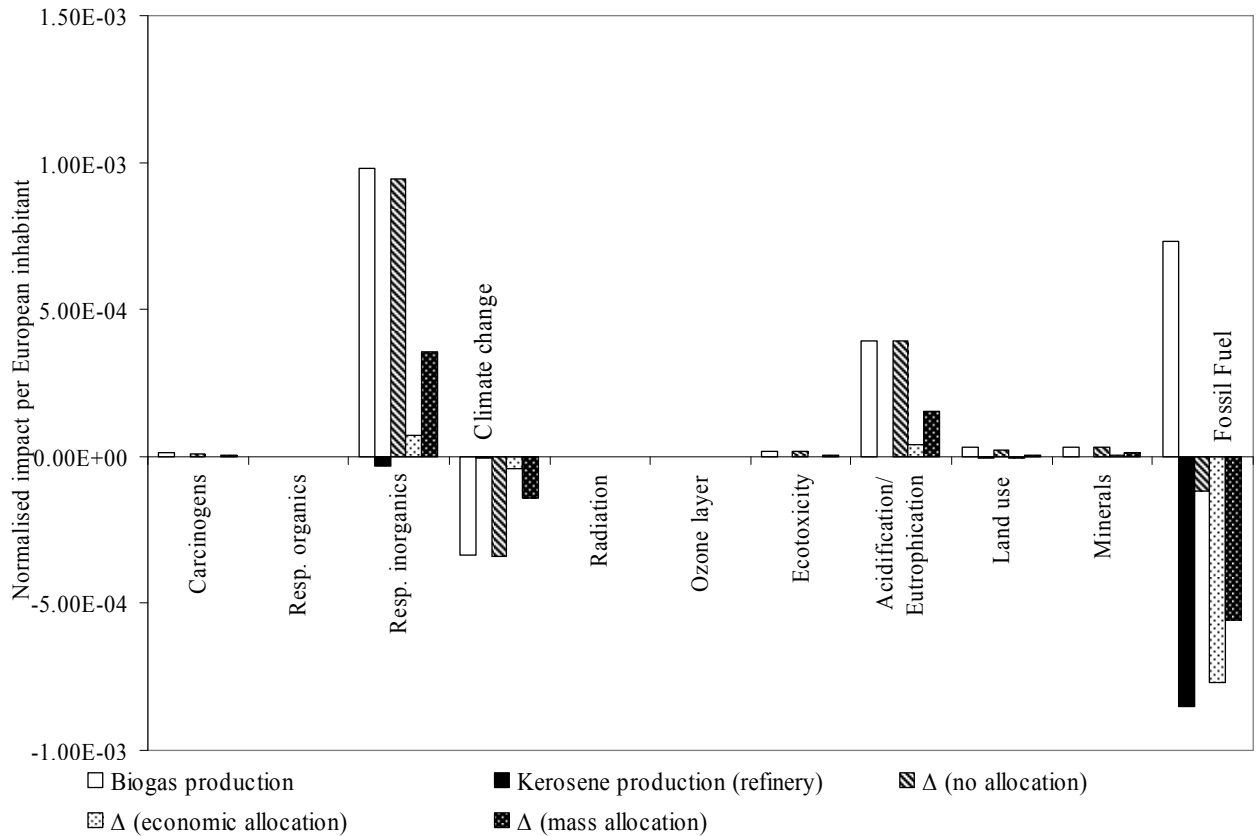


Figure 8-7 Normalised data for biogas production and avoided kerosene production

Analysing the biogas impacts based on the different allocation methodologies showed increased benefits towards the impact of fossil fuel resources. This was because the allocation methodology reduced the fossil fuel consumption for biogas production. If economic allocation were to represent the normalised outputs, the environmental benefits would be improved due to the small allocation given towards the biogas production.

A second analysis was carried out for the combustion of biogas used for domestic heat production. The avoidance of combusting kerosene was also analysed. Emissions for both energy sources were modelled using data from Table 8-3 and Table 8-4. The normalised results are displayed in Figure 8-8. The result of using both allocation methodologies was also shown. Overall, the LCA suggested that combusting biogas reduced impacts towards fossil fuel resource depletion and climate change. However, depending on the allocation methodology chosen, the savings ranged from 55% for impacts on climate change and 76% for impacts on fossil fuel resource depletion.

The results shown in Figure 8-8 suggest that adopting an economic allocation offered a smaller benefit towards climate change which was not seen when using mass allocation. This was the reverse for fossil fuel resource savings, even though the allocation was applied equally to all the impact category results. This was because the production of biogas (which included some *combustion* of biogas) showed a net saving in contributions towards climate change. This clearly showed how the choice of allocation could change the results significantly.

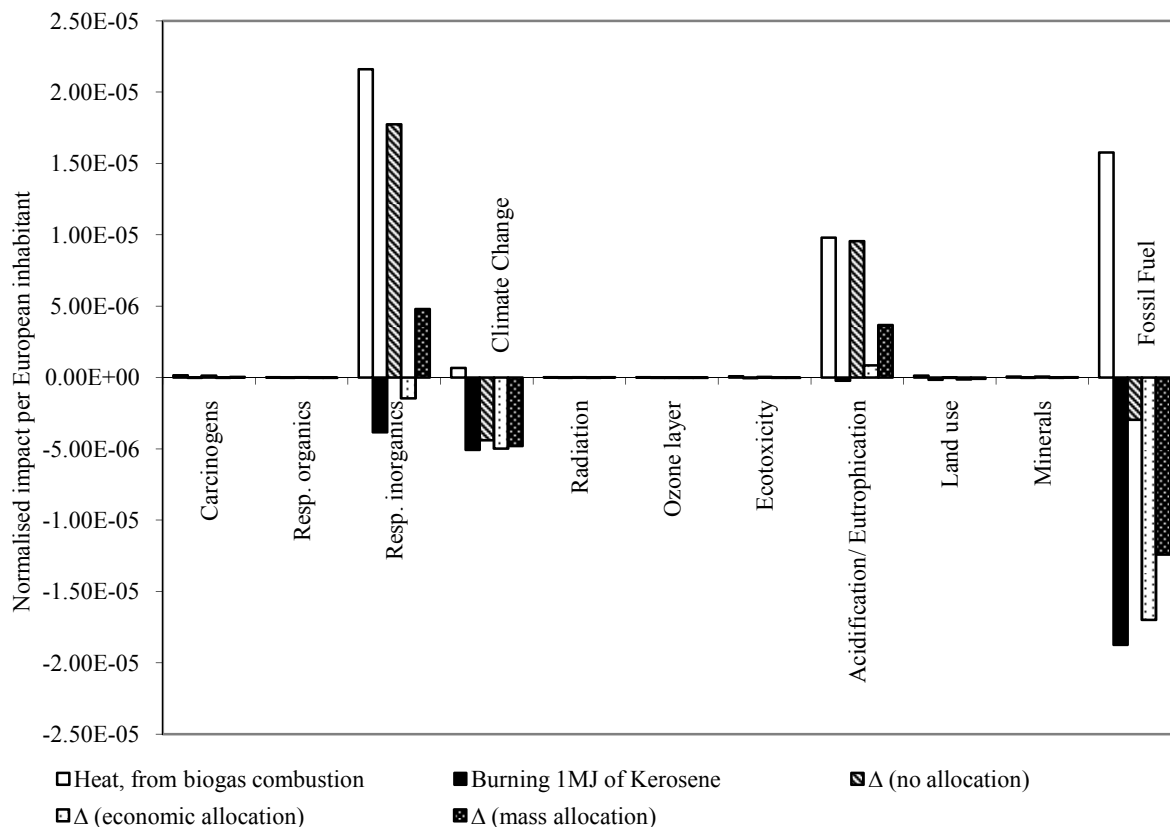


Figure 8-8 Normalised data of biogas production and combustion and avoided kerosene production and combustion

8.8.2 Environmental impacts of displacing inorganic fertilisers

The final analysis examined the production of the digestate and compared this against the displacement of inorganic fertiliser. The results in Figure 8-9 show the normalised data of the impact categories for the production of digestate as a fertiliser. The production of the digestate was calculated to displace artificial N, P₂O₅ and K₂O and therefore these results were negative. Displacing the use of inorganic fertilisers significantly reduced the use of fossil fuel consumption and hence the effect on this impact category. The fossil fuel resource savings occurred from the displacement of natural gas requirements, predominately for the production of ammonia which was then used for the ammonium nitrate fertiliser. Additionally, significant quantities of heavy oils were also used during the production of these fertilisers.

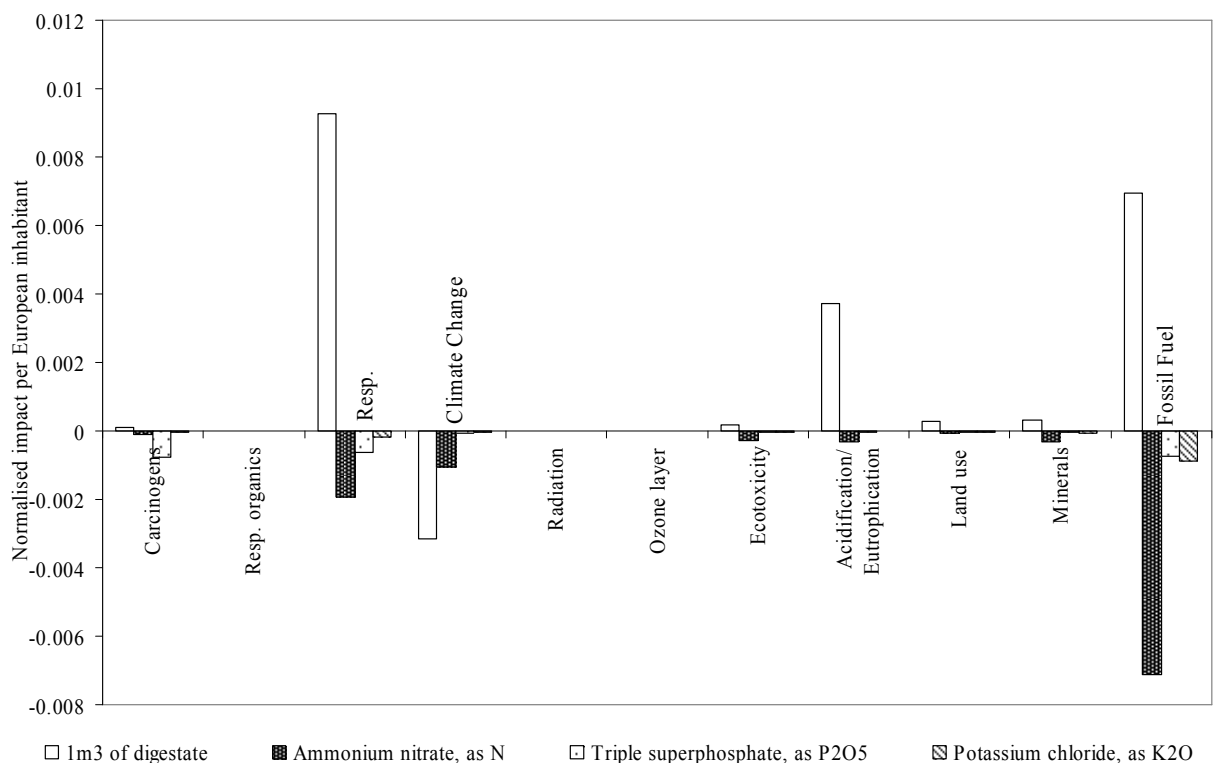


Figure 8-9 Normalised data of digestate production vs. inorganic fertilisers

Other significant savings occurred from the reduction in impact towards climate change. This was primarily due to the reduced production of nitric acid used in the manufacture of ammonium nitrate. The production of nitric acid requires high pressure and high temperature steam, which can reach up to 900°C (EFMA 2000). Steam production for this process was understood to be from natural gas (Althaus et al. 2007). However, the significant savings in the impact category 'climate change' were derived from the use of carbon dioxide as a resource from the organic matter. Although there were significant reductions amongst some impact categories, the displacement of inorganic fertilisers contributed detrimentally towards other impact categories such as respiratory inorganics and acidification (Figure 8-10). This was due to the emissions created during the operation of the plant, as discussed previously.

The data highlighted the overall effect towards each impact category, taking into account the allocation of the multi-output process. Overall, the use of the digestate offered benefits towards eight of the 11 impact categories. However, the two impact categories where the

digestate production contributed detrimentally were also amongst the most significant when normalised (respiratory inorganics and acidification). This was mainly due to the combustion emissions within the AD plant in order to heat the digester and the storage of the digestate. However, when a mass allocation was used the contribution towards respiratory inorganics and acidification/ eutrophication was halved.

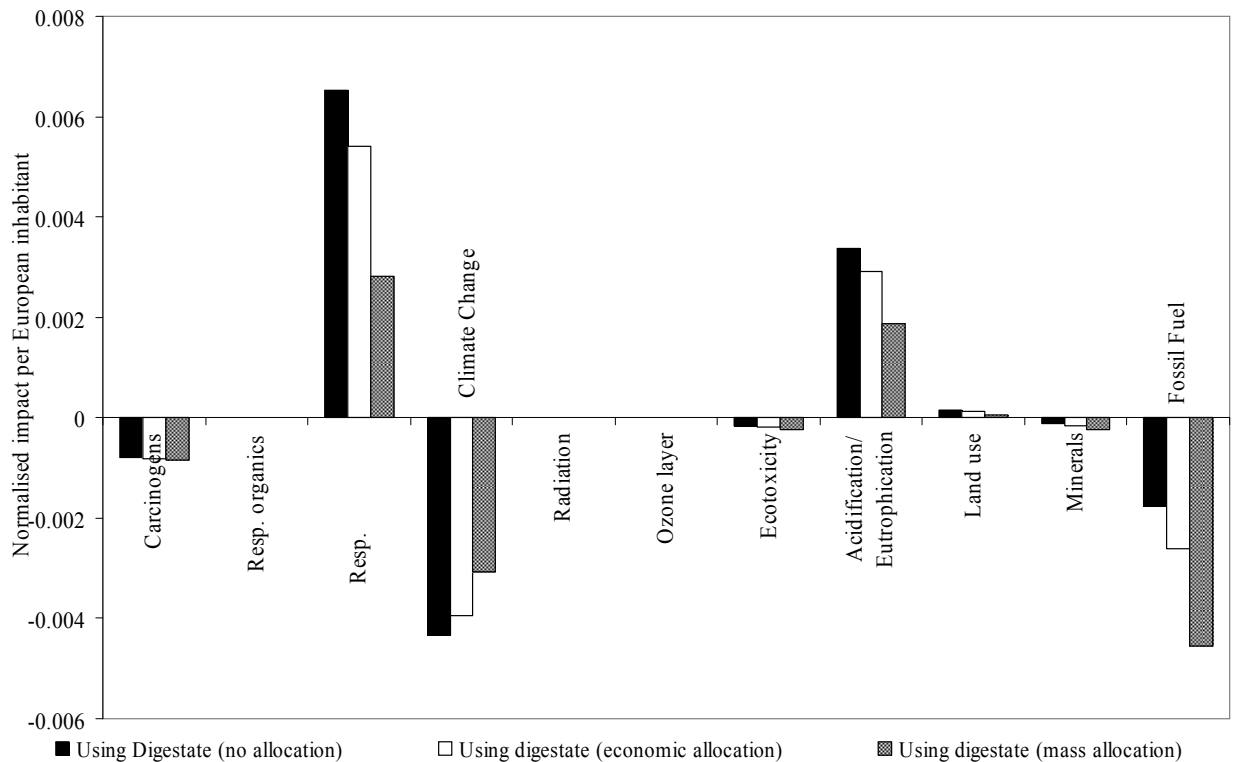


Figure 8-10 Normalised data - Net contribution of digestate as an inorganic fertiliser replacement

8.9 End-of-life of AD plant

In order to complete the LCA the end-of-life stage must also be considered. However if the plant life has not terminated, the end-of-life cannot be assessed as the analysis would have to be carried out in a future scenario. As a result, the end-of-life of the AD plant was considered outside of the system boundary and therefore not required for the study.

8.10 Whole lifecycle impact assessment

The whole life cycle for the two separate outputs of AD has been examined in this section. In these two figures (Figure 8-11 and Figure 8-12), the mass allocation of impacts were used, rather than economic. Over an operating life of 25 years, a mass allocation would have no fluctuation, whilst an economic allocation could change depending on fuel and fertiliser prices. As a result, economic allocation was not considered a suitable option for modelling whole-life.

Figure 8-11 shows that over the whole life of biogas production, the emissions from the plant use contributed the most towards three environmental impact categories: respiratory inorganics, acidification/eutrophication and fossil fuel resource depletion. Over the life of the plant, the AD process produced enough emissions to have an impact equivalent to between 20-60 European inhabitants per year. The plant construction was also found to have

insignificant contributions towards the environmental impacts, when compared to the use phase of the AD plant. These emissions were produced only once within the lifetime of the plant, whilst plant use had reoccurring emissions.

The most significant result came from the displacement of the kerosene production, using biogas. The energy equivalent of kerosene showed a significant reduction in fossil fuel resource depletion over the life of the AD process. Additionally, savings in CO₂ emissions also contributed towards a reduction in climate change impact, giving the plant an overall (net) negative output on climate change.

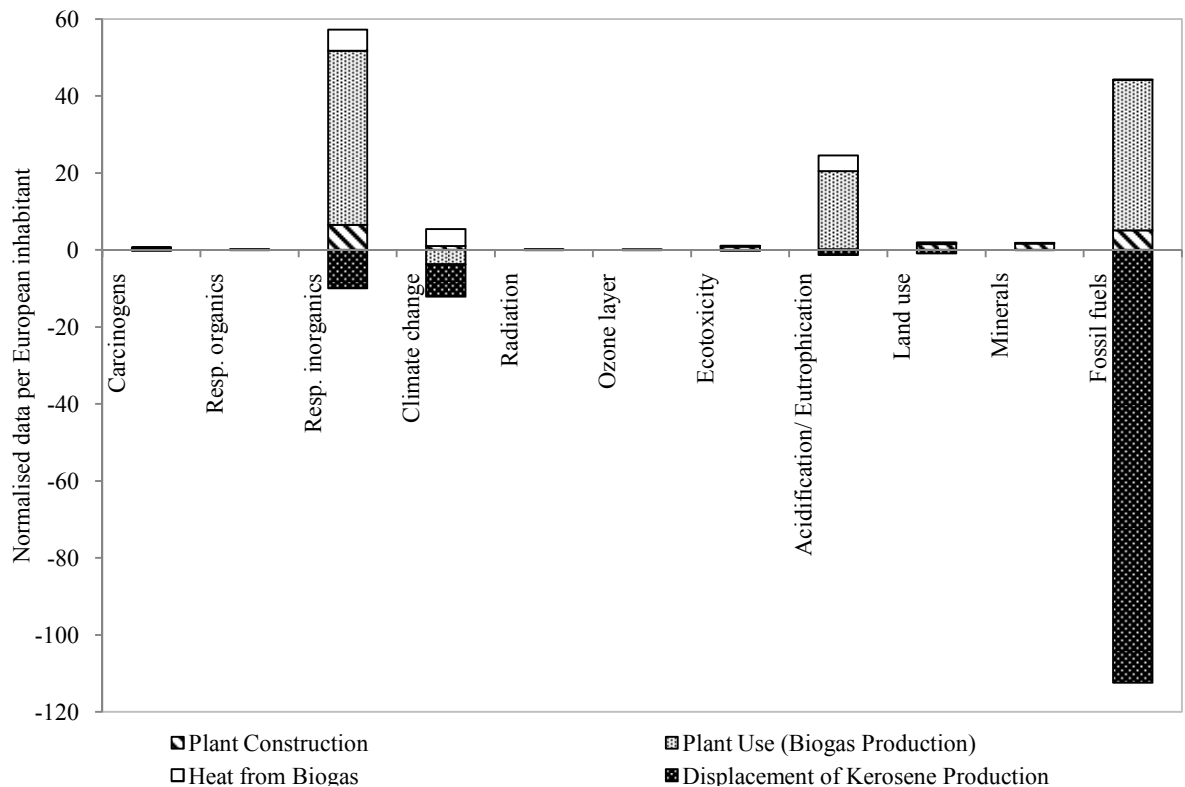


Figure 8-11 Normalised data - Whole lifecycle environmental impacts of biogas

Figure 8-12 shows the whole life normalised environmental impacts for the digestate output of the AD process. These results also highlighted that the AD plant use phase contributed significantly towards respiratory inorganics, acidification/eutrophication and fossil fuels resource depletion. However, due to the mass allocation, the emissions allocated towards the digestate production were higher. As a result, the overall contribution of the emissions towards these environmental impact categories was more significant. Over the life of the plant the emissions associated with the plant construction had minimal contribution towards the environmental impact categories, which was similar to the biogas production lifecycle.

The most significant contribution towards the whole-life cycle of the digestate output from AD was the savings in displacing inorganic fertiliser. Based on the same quantity of fertiliser (in terms of N, P₂O₅ and K₂O properties) the displacement of inorganic fertiliser resulted in a significant reduction in impacts towards four main environmental impact categories: carcinogenic effects, respiratory inorganics, climate change and fossil fuel resource depletion.

Overall the key benefits from digestate displacing inorganic fertiliser were savings in fossil resources which also led to a reduction in carbon emissions (and a lower impact on climate change). Additionally, other smaller benefits across most of the environmental impacts were also seen.

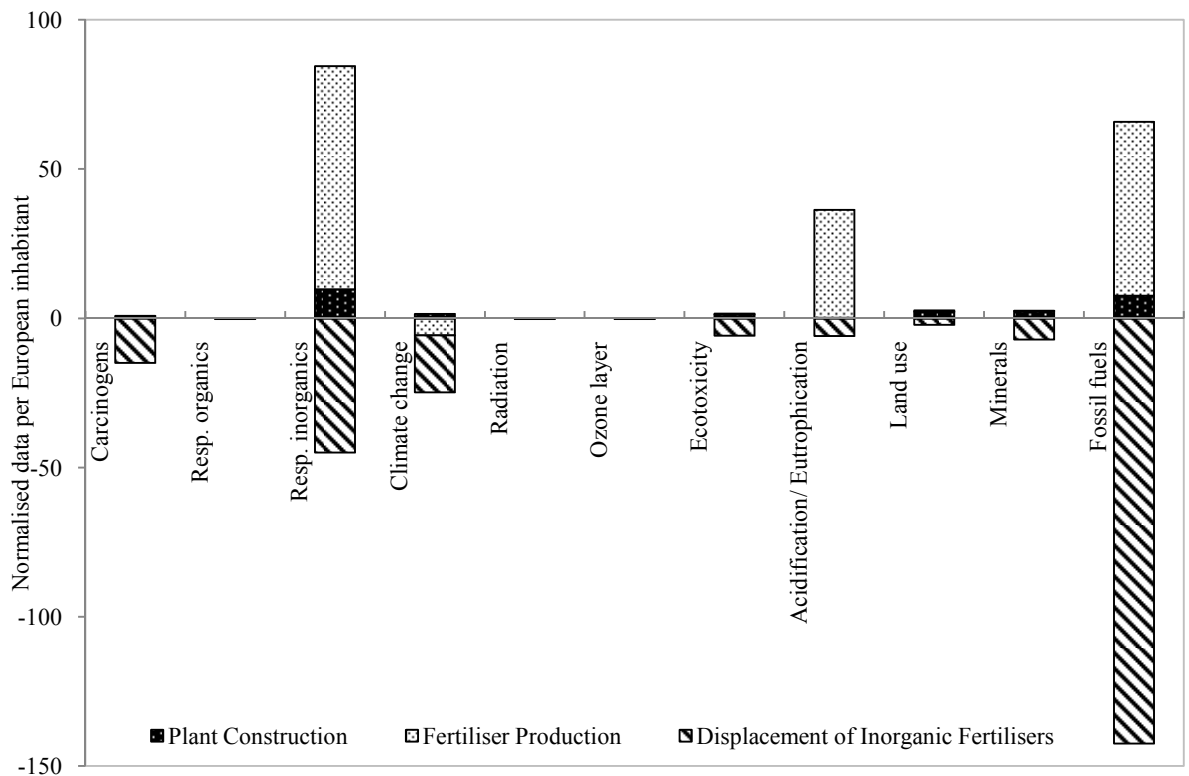


Figure 8-12 Normalised data - whole lifecycle environmental impacts of fertiliser (digestate)

The common factor between both lifecycles was the high emissions contributing towards respiratory inorganics and acidification/eutrophication. These emissions, produced during the use phase of the AD plant, could have a detrimental impact towards human health and ecosystem quality. It also appeared that although there were savings in kerosene and inorganic fertilisers, these impact categories were still significant.

The emissions leading to respiratory inorganics were from the digestate storage, the combustion of kerosene, diesel and biogas. These emissions can cause smog leading to respiratory effects such as asthma, chest infections and bronchitis amongst other chronic obstructive pulmonary disorders. As a result, these emissions could have serious effects on human health.

Acidification can have a severe impact on ecosystems through the increase in the pH acidity of waters and soils. Air emissions can also lead to acid rain which can have detrimental effects especially on vegetation (for example conifer trees can seriously deteriorate in health through acid rain). Eutrophication can lead to an abnormal increase in nutrient concentration over specific soil or water volume. The increase in nutrient availability increases the growth of aquatic plants and algae. An overproduction of algae and blooms causes an increase of plant life on the water surface, which can lead to reduced sunlight and oxygen penetrating the top layer of water. Increased nutrients in soil can lead to leaching into water streams causing

eutrophication of lakes, rivers or bathing waters (J. Gascoigne, Greenfinch 05/05/2008, personal communication).

This shows how emissions from an industrial process such as AD could have detrimental impacts on the delicate balance of natural species and also human health. The detrimental environmental impacts affected by the use of AD can have direct or indirect impacts towards human health and ecosystem quality. Measures should be taken to minimise the emissions within the AD process. Reducing these emissions could minimise the overall environmental impact of the AD process, which is significant if the technology were to be used on a large scale.

8.11 Sensitivity analysis of study

This section reports the work carried out to assess the uncertainty of input data for the LCA. The LCIA results have highlighted the most significant environmental impact categories. From here it has been possible to determine the emissions relating to these impact categories and subsequently the cause (or source) of these emissions. The sensitivity analysis therefore examines the emissions, which have had the highest contribution towards the impact categories.

Although the LCA clearly demonstrated the environmental performance of using an AD plant to produce biogas and fertiliser, the results were dependant on the input data quality. LCA has been described as a black box (Bras-Klapwijk 1998) due to the lack of transparency of how the input data is transformed into relatively easy to understand environmental impacts. The significance of the choice of LCIA methodology also has a large impact on the output results of an LCA. In fact, studies from Sonnemann et al. (2003) highlighted the ambiguity of using the weighting procedure within LCA.

As a result of these uncertainties, the valuation (through weighting of the impact categories) was not carried out in order to minimise subjectivity errors. However, the other source of uncertainty originated from the quality of data input at the LCI stage. Throughout the study, a number of assumptions and calculations were made due to not having accurate actual plant data. The effect of these errors was examined through a sensitivity analysis.

8.11.1 Sensitivity analysis of plant manufacture

The weights attributed to the components within the plant manufacture were mainly derived by reproducing a 3D computer model of the main parts of the AD plant. The analysis of the software modelling and the LCA suggested that the majority of the environmental impacts were derived from the steel consumption. Therefore, a sensitivity of the steel used within the plant was carried out.

The steel consumption was primarily used for the digester and digestate tank. The selected wall thickness for the tanks was 12mm as stated on the manufacturer's website (Permastore 2009). However, this data was accessed in March 2008 and at the time of writing the data was no longer available. Having contacted another manufacturer (Kirk Environmental Ltd. 24/09/2009, personal communication), it was found that wall thicknesses could range between

2-10mm and could be double-fitted creating a wall thickness of 20mm. Following extensive discussions with the technical department it was determined that a more suitable wall thickness for the tanks in question could be around 9.5mm in thickness. This could be reduced even further for the digester tank. It was concluded by Kirk Environmental Ltd. (24/09/2009, personal communication) that a 12mm wall thickness was approaching the upper range as a design safety factor. The analysis examined a change in 50% of the wall thickness, thus varying between 6mm to 18mm. Table 8-8 shows the variation in mild steel use if the wall thickness varied between 6-18mm. Although wall thickness could be as low as 2mm, this was considered improbable due to the size of the plant.

Tank Wall thickness	Digester Tank (kg)	Digestate Tank (kg)	Reception Tank (kg)	Total (kg)
6mm	17,398	37,995	6,376	61,769
12mm	22,307	46,323	8,379	77,009
18mm	32,135	62,966	12,374	107,475

Table 8-8 Plant steel use depending on wall thickness

With a 50% variation in wall thickness, it was apparent that there were differences in contribution towards all impact categories. The change affected the overall steel consumption by up to 43% between the maximum and minimum. The results, shown in Figure 8-13, highlight the greatest influence on the impact categories of 'respiratory inorganics' and 'fossil fuel depletion'. Increasing the use of steel in the plant manufacture increased the contribution to fossil fuel depletion of just under 30% due to the increased energy consumption in manufacturing and processing the steel. This increase in steel production would increase the damage to respiratory inorganics by 32%.

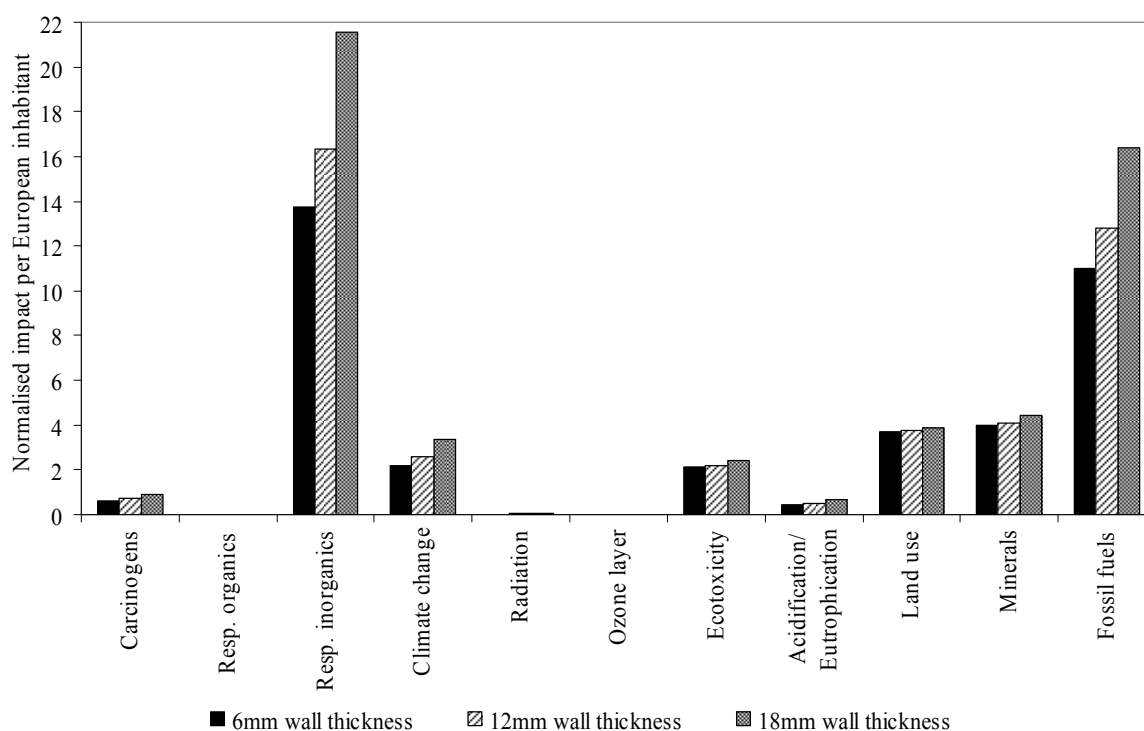


Figure 8-13 Normalised data for AD plant manufacture. Sensitivity analysis on steel consumption

The second stage of the sensitivity analysis examined the composition and production of the steel used within the LCI. The steel manufacture analysis assumed 100% of the steel was primary virgin steel. This was replicated through the results as a significant amount of the carcinogenic effects was contributed at the iron ore recovery stage. If recycled steel were used (or at least a percentage were used), then some of the impact category contributions could be lower.

According to leading UK steel manufactures, the average recycled content in steel was around 54% (Corus 2007). However, according to the Government backed Waste & Resource Action Programme (WRAP), recycled content in steel sections are considered to be 60% in the UK (WRAP 2008). The analysis therefore assumed an uptake of 60% recycled steel, with the remaining 40% originating from primary sources. The recycled content of the steel was assumed to be derived from iron scrap which was collected from waste disposal sites, sorted and pressed into usable blocks. The LCI data for producing recycled steel was obtained from the EcoInvent database and was representative for a European scenario (Swiss Centre for Life Cycle Inventories 2007).

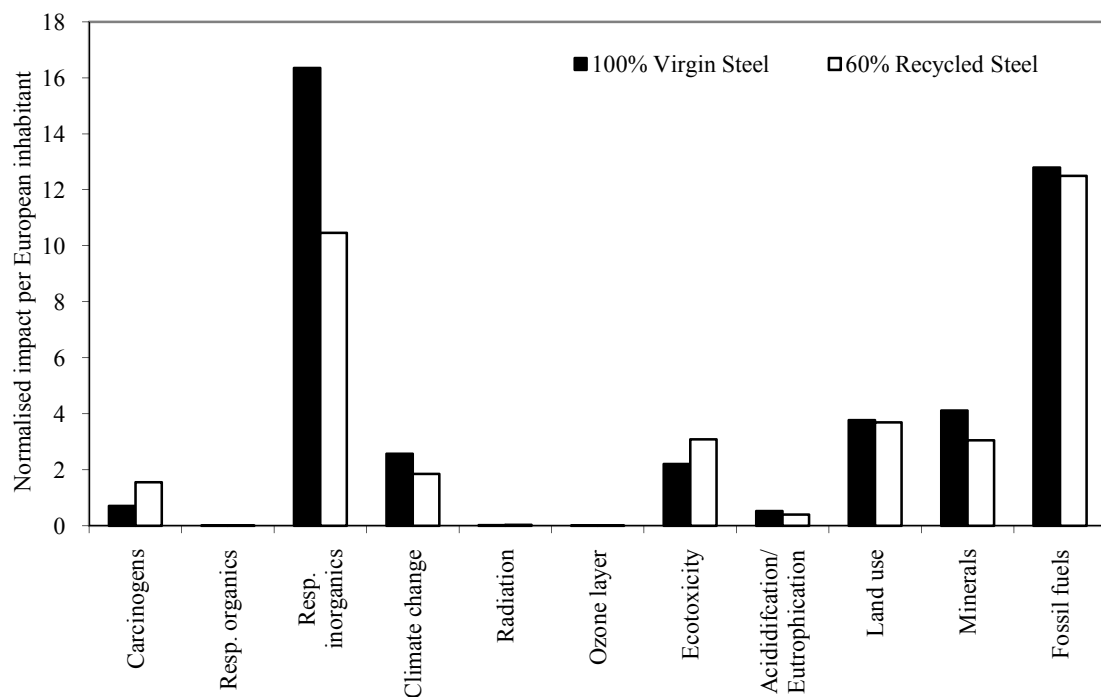


Figure 8-14 Normalised data of plant manufacture. Sensitivity analysis on % of recycled steel use

The results shown in Figure 8-14 highlight a reduction in contribution towards respiratory inorganics of around 40% through the use of recycled steel. However, the other major impact category (fossil fuel resource depletion) remained relatively similar with a small reduction only. This was due to the relatively high fossil fuel consumption used for energy production during the reshaping of scrap steel into useable steel. In addition to this, the hot rolling process used in the manufacture of the tanks was unaffected by the composition of the steel. The latter contributed significantly towards the impact category 'fossil fuel depletion'.

8.11.2 Sensitivity analysis of plant use phase

Throughout the analysis, it was discovered that a number of uncertainties in the plant use phase could lead to a large change in contribution towards the impact categories. The largest contribution towards the impact categories was determined to be derived from the emissions produced during the digestate handling and the combustion of the biogas and kerosene to heat the digester. Emissions from diesel burning were also found to have a large contribution towards these impact categories.

The impact category 'respiratory inorganics' was primarily affected by ammonia, sulphur dioxide, nitrogen oxides and particulate matter emissions. Within the literature sources, the emissions for sulphur dioxide from kerosene combustion varied between 23mg/MJ up to 3360mg/MJ (Niels et al. 1997; Spielman et al. 2007a). However, the latter was considered unrealistic for typical kerosene combustion as this represented combustion of unrefined kerosene for rural cooking in India.

The sensitivity analysis concluded that these emissions could have a feasible standard deviation of between 40-60% of the chosen average value. As a result, emissions from digestate storage, biogas and kerosene combustion (sulphur dioxide, nitrogen oxides and particulates) were varied by an average of 50% to determine the effects this had on the overall biogas production contribution towards the impact categories. For example, ammonia emissions from digestate storage were varied between a maximum 0.039 kg/m³_{biogas} to 0.0102 kg/m³_{biogas} as this was the range found within the literature (Deublein & Steinhauser 2008).

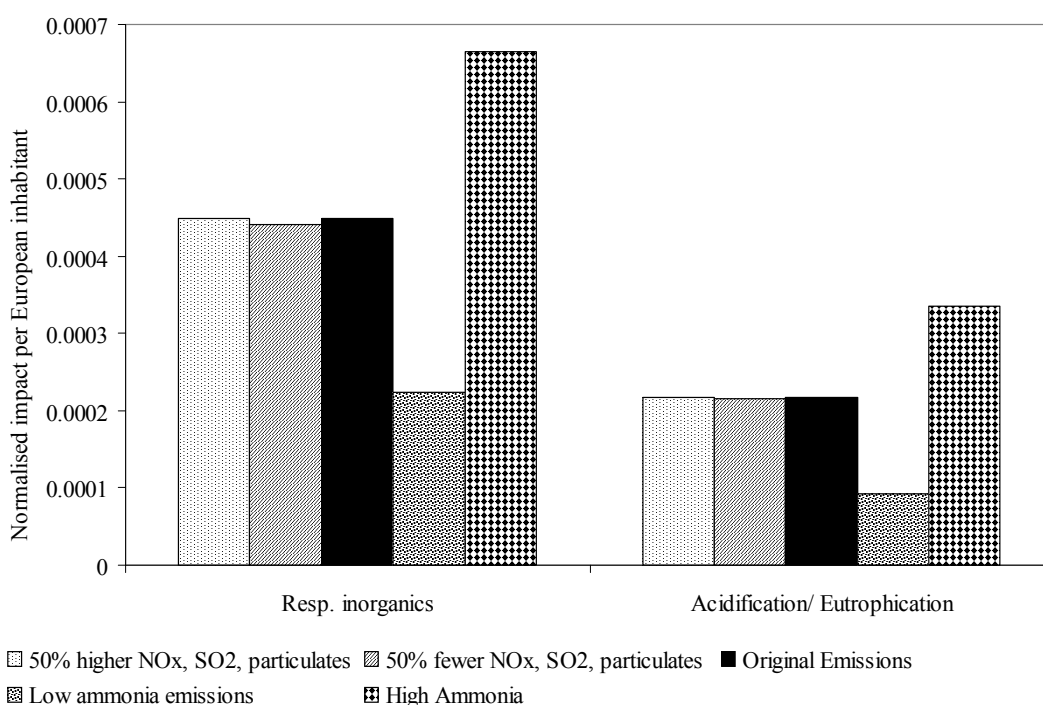


Figure 8-15 Normalised data for two impact categories. Sensitivity analysis of air emissions

As shown in Figure 8-15, the change in emissions from biogas and kerosene combustion made little change towards the two impact categories. However, the change in ammonia had a significant variation by over 50%. In fact, AD studies used within the EcoInvent database used a value 35% lower than the ammonia value chosen in this study (0.0102 kg/m³_{biogas}). Therefore,

it was concluded that the value for ammonia emissions had the largest impact on the sensitivity of the respiratory inorganics and acidification results.

The final stage of the sensitivity analysis examined the impacts contributing towards fossil fuel resource depletion. Throughout the use phase of the LCA, this impact category appeared to be amongst the most significant across the normalised data results. The fossil fuel resource consumption was derived from the kerosene used for plant start-up and the assumption of diesel consumption for farm handling equipment.

Although an assumption was obtained from Spielman et al. (2007b) of 18 MJ/tonne of diesel used for feedstock handling equipment, no specific machinery was observed on site at the time of the visit. Therefore, one could assume that no machinery would be required as the cattle housing was situated in close proximity to the reception pit tank. Additionally, if the collection of the digestate were considered outside of the system boundaries then the diesel use within the AD plant would be zero.

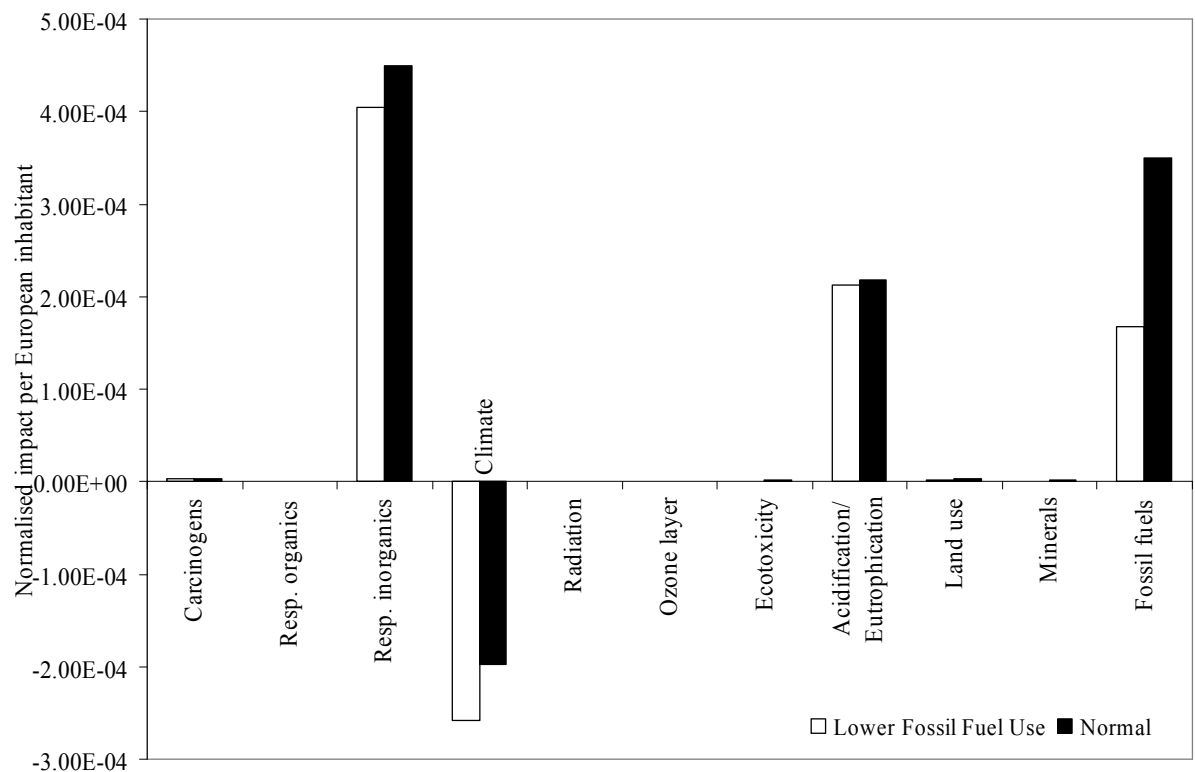


Figure 8-16 Normalised data of biogas production. Sensitivity analysis of fossil fuel consumption⁴

The kerosene used for start-up was also applied to an AD plant with a greater operational output. By calculating a maximum capacity factor for the feedstock availability, this changed from 14% to 28%. This meant that the same amount of kerosene (1,500 litres) could have been used for nearly double the output in biogas. It was assumed that more kerosene use would not be required as the downtime of the plant would be less. Using these assumptions, the sensitivity analysis showed that in terms of normalised data, the contribution towards fossil

⁴ Note: negative climate change occurs due to the carbon fixation within the biogas. This will be released once the biogas is combusted

fuel resource depletion was reduced by 52%. The overall contribution towards all the impact categories of using fewer fossil fuels has been shown in Figure 8-16.

The condensed use of kerosene and diesel was significant for reducing the contribution towards fossil fuel resource depletion. However, this also affected the climate change impact as fewer CO₂ emitting energy sources were used. This was also true for the affect on respiratory inorganics due to the decrease in particulates, NO_x, NH₄ and SO₂ emissions.

8.12 Summary

The study analysed the environmental impacts of biogas production and utilization through the technique of life cycle assessment (LCA). LCA enabled an understanding of the factors which contributed most towards detrimental impacts on the environment, during the life cycle of biogas production. The study also examined the environmental benefits of using biogas as a domestic heat source, subsequently displacing the use of domestic heating kerosene fuel. Due to the data intensiveness of LCA, it was accepted that there could be a significant percentage error amongst the results. Consequently, a sensitivity analysis was undertaken on datasets, which were recognized as having the most significant impacts. The key findings from the LCA results can be summarised:

- The emissions created from the plant manufacture contributed very little towards the whole life cycle environmental impacts. This would have been further reduced if a higher operating capacity factor were obtainable.
- The use phase of the AD plant created emissions which appeared to have significant impacts towards human respiratory systems and acidification/eutrophication issues within ecosystems.
 - The impacts were a result of emissions such as ammonia from the digestate storage, sulphur dioxide, nitrous oxide and particulates from the combustion of biogas, kerosene or diesel.
- The production of biogas and fertiliser both created significant impacts towards fossil fuel depletion due to the use of diesel and kerosene. However, over the whole life cycle, the displacement of kerosene as an end-use energy source and inorganic fertilisers, showed a net-benefit in fossil fuel depletion.
- The study concluded that it is essential to cover the digestate storage tank as biological reactions are still occurring thus emitting, methane, ammonia and carbon dioxide. Globally a number of AD units do not cover the digestate storage.
- De-sulpharisation and ammonia removal processes were also considered to be crucial within the AD system in order to remove these emissions either entering the atmosphere directly or undergoing the combustion process.
- Ammonia is also released during the spreading of digestate. However, as the lifecycle system boundary terminated at the fertiliser production stage, this was not included. This could however be included as a further analysis.

9 FINANCIAL INVESTMENT APPRAISAL OF BIOGAS PRODUCTION

9.1 *Introduction*

The third and final stage of the multi appraisal technique was to assess the potential of biogas using financial appraisal techniques. This chapter discusses the implementation of a Financial Investment Appraisal (FIA) on the use of AD. The chapter highlights the financial payback period, the net-present value and the benefit-cost ratio of different AD setups.

The study follows two levels of examination. The first was to assess the economic performance of a number of existing operational AD plants, thus examining the cost against a number of parameters. The second level of examination was to assess in detail two AD plant case studies (Plant A and Plant C), which have been used throughout the multi appraisal technique (Chapter 7 & 8). These case studies were examined using current financial data for the UK.

9.2 *Aim and purpose of study*

The aim of the study was to determine the success of biogas production from a financial perspective. An FIA was carried out on two of the case studies to examine how different set-ups performed. These case studies were chosen based on the results obtained from previous analyses and the suitability for use within the South West of England. As biogas can potentially be used for a variety of energy-end-uses, a further FIA was performed on differing energy pathways. The study evaluated the effects of the new ROC banding and the feed-in-tariffs (FIT) for renewable electricity.

In this study plant A and plant C were analysed. Plant A is a small-scale AD plant situated in the UK fed solely on animal manure. A description of these plants can be found in section 5.1. The use of FIA for biogas production in general was also carried out and shown throughout the chapter. This included assessing and reviewing a number of software models commercially and publically available, used for assessing the financial feasibility of biogas production. Financial data for a number of operating AD plants in Germany (FNR 2005) was also assessed, to examine patterns and trends between parameters such as digester size versus capital costs.

The FIA subsequently examined the financial implications of adopting biogas for different end-uses. Following this, it highlighted the different financial incentives and policy drivers which are in place in order to develop the use of biogas as an energy source.

9.3 *A review of biogas economic simulation modelling software*

Due to the multiple benefits envisaged with AD there has been a growing interest in the financial feasibility of AD development. As a result, a number of economic costing models have been devised either through academia or through direct Government funded initiatives. These models are capable of simulating a theoretical AD plant setup, examining the performance and costs of the plant depending on the parameters inputted into the models. The models researched have been briefly described in the following section.

Farmware 3.0 (available from www.epa.gov/agstar/) – This is an economic model for AD plants created by the US Environmental Protection Agency. It is free to download and operate.

The model is extremely detailed in the parameters which the user can input. All economic factors can be inputted such as the down payment percentage, interest rate values, discount rate etc. The model can only simulate two types of manure: cattle and pig waste. However, the model also simulates the climatic conditions depending on the location of the plant, thus affecting the energy requirement of the plant. The user can also specify the use of the biogas and details the breakdown of the costs.

Andersons National Non-Food Crop Centre (NNFCC) model (Redman 2008) – This model is designed for UK AD operations. It has a much greater range of input feedstocks and can also model the effects of growing and supplying dedicated feedstocks. The model is more ‘open’ than Farmware and therefore the user can clearly see how each stage is calculated.

Government financial support mechanisms are also incorporated into the model. The model therefore gives detailed analysis of the profit and loss for theoretical AD set-ups. Although the model is not location dependant, it can simulate the effects of adopting biogas for heat, power or transport fuels.

BEAT model (available from www.biomassenergycentre.org.uk) – This model was created by the UK Environment Agency, primarily to model the emissions of biomass projections. The model is not AD specific; however it can compare the use of AD against other energy forms of the same end-use. However the model is the most simplified out of the ones tested and although it has the function to state whether the plant is centralised or farm-scale, it does not let the user input the daily feedstock quantity. The costing analysis of the model is also not as advanced and detailed as the previous models. Within the foundations of the model, the methane quality per cubic metre of biogas is more optimistic than literature findings. A 65% CH₄ concentration per cubic metre of biogas from cattle waste is around 5-10% higher than literature findings (Ecofys 2005; Fan et al. 1985). The model also does not simulate the use of biogas as a vehicle fuel, whilst only modelling heat and/or power.

Ghafoori & Flynn (2007) AD models – The model is based on AD plants situated in Canada and does not take into account climatic conditions. The software is divided into two separate models (large scale and small scale). A unique feature of this model is that it takes into account the transport distances of the feedstock, which as found in previous chapters, can be a significant sink when assessing energy flows within AD plants. The model is similar to the NNFCC model, as it is ‘open’ layout, enabling the user to change most of the parameters associated with the AD plant. This also includes discount rates, maintenance cost percentage allocation and other variables.

As can be seen from the literature findings, detailed modelling of financial investment appraisals for AD is available and abundant. Therefore, a detailed analysis of the basics of AD economics is not required. However an understanding of the factors which affect the financial viability of AD should be made, in order to assess its potential for deployment within the South West. As a result a tailored financial model was created for two plant case studies (Plant A and Plant C). The model examined the financial performance of the plants using a range of parameters and correlations obtained from literature sources which have been referenced where appropriate.

9.4 Cost analysis of biogas production and use from AD

The implementation and use of biogas production technologies incurs costs throughout the supply chain similar to other bioenergy pathways. Costs may be classified into four key areas: investment costs, operational costs, insurance and taxes and costs associated with handling the feedstock off-site (Ecofys 2005). Investment costs are common amongst any renewable technology; however bioenergy pathways differ as they also incur significant operational costs during their lifetime. In the case of AD these costs are incurred through the operation and management of the plant, handling of the feedstock to and from the plant and maintenance of the plant components such as digester, piping, pumps and valves and the CHP unit (if one is installed). The following sections describe how these costs are incurred and the parameters which affect them.

9.4.1 Cost analysis of plant manufacture

The use of agricultural AD in the UK is extremely limited, with around 16 installed and operating plants. In other countries, such as Germany and Austria, the numbers of AD plants are around 3,700 and 309 respectively. Due to the limited use of AD in the UK, the basis of the financial data was derived from operational German AD plants.

Capital costs within literature have been reported to be £2,500 to £6,000 per kW of installed electricity generating capacity (Redman 2008). Capital costs from the data obtained for this analysis averaged around €3,000 per kW of electrical capacity (roughly equivalent to £2,600/kW). As some of the plants operated a CHP unit, a capital cost per electricity output was considered misleading. Consequently, a capital costs per unit methane output was calculated. This value averaged around £500/m³ of methane per day.

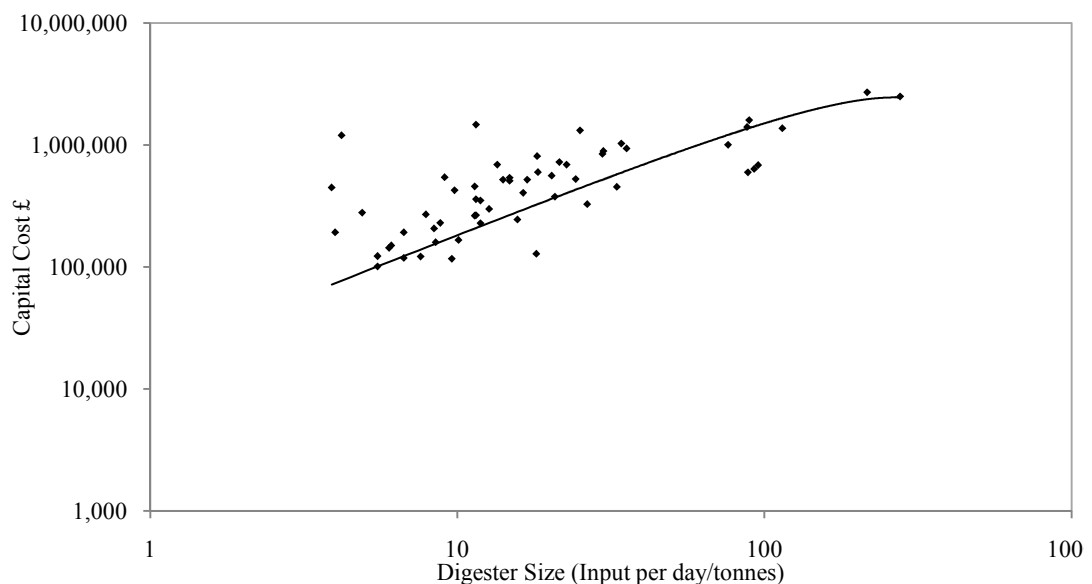


Figure 9-1 Capital costs of AD plants vs. daily feedstock input capacity- Data from 60 operational AD plants (FNR 2005)

Further analysis of the German AD plant data showed that there was little correlation between the daily biogas output (and methane output) and the capital costs of the plants. A much closer correlation was obtained when examining the capital costs of a plant against the daily input feedstock. The results in Figure 9-1 show a linear correlation of increase in capital costs versus the increase in daily input of feedstock into the plant. The capital cost for these plants averaged around £20,000/tonne/cubic metre of feedstock input.

The costs associated with AD set-up were found to be primarily associated with the digester tank manufacture and installation. From the literature the cost of the digester was found to be around €50/m³ (£43/m³) for a digester tank and €30/m³ (£25.5/m³) for a digestate tank (Ecofys 2005). According to this source, CHP units were also a significant expense. The installation costs for CHP units were said to vary between €360/kW to €1,200/kW installation capacity (£310/kW to £1040/kW). Consequently, the CHP unit could account for 12-40% of the total capital investment (*ibid*).

The setup costs can vary significantly depending on the equipment and requirements adopted. For example, a simple animal waste AD plant would not require the use of a pasteurization facility. Other plant equipment, which may or may not be adopted for biogas production include hydrogen sulphide reduction systems, post-digestion solid separation systems which separate the fibrous fraction of the waste (used as P-fertiliser) from the liquid fraction of the waste (used as N-fertiliser) and other gas cleaning equipment.

The requirement for a CHP unit is necessary solely for electrical power and heat generation. Some plants (albeit not a great deal) use the biogas exclusively for heat use. This is the case for the case study plant A used throughout the multi appraisal technique. Infrastructural costs for this technique are significantly lower (J. Gascoigne, Greenfinch 05/05/2008, personal communication). In these cases, the biogas is pumped into conventional gas boilers and combusted. The minimum required methane quantity within the biogas, in order for it to ignite, is around 45% (J.Prior, Summerlease ltd. 22/05/2007, personal communication).

Amongst some literature sources it was observed that setup costs decreased as the daily production rate increased (Murphy & Power 2009). According to their findings the financial output of biogas production at larger AD setups was more favourable than smaller installations. Although this may be true for the setup costs, greater biogas production would ultimately require a greater availability of daily feedstock. This could result in increased feedstock collection and transport costs during operation. Therefore, there is a trade-off between the setup and operational costs and the expected biogas output of the plant.

For the purpose of this study a capital cost of £20,000/tonne of daily feedstock input was used. Using a capital cost in relation to daily feedstock input was seen as a more accurate measure than relating it to the biogas output. The biogas output is dependant on the efficiency and feedstock of the plant and therefore can also be misleading.

9.4.2 Cost analysis of AD plant operation and maintenance

Operating costs associated with AD plants were found to include general operation (water, electricity, heat and other energy required around the plant), maintenance costs, labour costs and unexpected downtime costs (Deublein & Steinhauser 2008). The main costs associated

with operation of the AD plant were found to be linked to electricity consumption, heat consumption and feedstock management.

The cost of heating the digester is often excluded as the heat from biogas combustion is utilised. This was true for all the German operating plants for which data had been obtained. However, costs were incurred during digester start-up, using kerosene. This was found to average around 2.3 litres/tonne of annual feedstock. Assuming a kerosene oil price of around 40ppl, this equated to £0.92/tonne of annual feedstock input.

When analysing the use of biogas for transportation fuel, an additional heating cost requirement was calculated. This is because the conversion of biogas to a transportation fuel does not produce waste heat as a by-product. If biogas were used as transport fuel, then external heat costs would be encountered, as biogas would not be combusted on-site. AD plants specifically operated for transport fuel production were found to have a cost of heat energy between £1.60-1.80/tonne of input feedstock (Murphy & Power 2009).

Other costs reported by AD owners included maintenance and servicing costs (J. Gascoigne, Greenfinch 05/05/2008, personal communication). Literature reports suggested a figure of around 2-4% of the total capital cost should be allocated to maintenance costs (Ecofys 2005). An analysis of operational AD plants showed that maintenance costs (including spare parts and labour) varied significantly. These costs were between €4,000/annum (£3,400/annum) on a capital cost of just under €500,000 (£425,000) up to €72,000 (£61,200/annum) on a capital cost of just below €1million (£850,000). Assuming an average life of 20 years, the operation and maintenance costs as a percentage of capital costs was around 8-14% (FNR 2008).

The largest impact on operational costs was found to be dependant on whether feedstocks had to be purchased for the plant operation. Manure production generally do not have a cost allocated to it, however purchasing substrate feedstocks such as wheat, grain or silage can be a significant contributor to operational costs. AD plants which operated using substrates were found to have a cost allocation towards substrates of between 15-60% of total operational costs (FNR 2005). Literature sources showed this percentage to be slightly lower at around 7% (Ecofys 2005). This is ultimately dependant on how much substrate is needed. Other sources showed that dedicated feedstocks could contribute up to 60% of the total operating costs (Murphy & Power 2009). Typical costs of feedstock from this source have been tabulated below in Table 9-1.

Biogas Feedstock	Cost (£/tonne)
Maize Silage	20.00
Grass Silage	18.00
Wheat (grain)	150.00
Barley (grain)	145.00
Pig Slurry	0.00
Cattle Slurry	0.00

Table 9-1 Cost per tonne of biogas production feedstock - (Redman 2008)

Literature suggests that one of the most influential factors affecting the uptake of AD in the UK and Germany is the use of dedicated crops for co-fermentation (Yeatman 2005). These energy crops include maize, grass, etc. Currently in the UK the main energy crop is oilseed rape (over 240,000 ha in 2007 (NNFCC 2008)). Oilseed rape is primarily used for biodiesel production, which in 2007 was nearly 300% higher than the use of bioethanol (EurObserver 2008). According to this source, the use of energy crops is extremely limited in the UK.

There are currently no AD plants in the UK which operate using energy crops as feedstock. UK plants appear to have a greater focus on using industry or general food waste as a feedstock where gate fees provide additional income. In fact some plants could not operate without this supplementary income (J. Prior, Summerleaze Ltd. 22/05/2007, personal communication).

9.4.3 Cost analysis of biogas conversion and transport

Using biogas as road fuel is an alternative to electricity and heat production. The biogas upgrade unit used to create road fuel can operate via a water scrubber technique or a pressure swing absorption (PSA) technique. Biogas upgrading is extensively used in Sweden, where in 2006 the use of biogas in road vehicles overtook the use of natural gas (Jönsson 2004).

Upgrading costs were found to vary significantly depending on the plant scale. However according to Jönsson (2004) the typical operating costs for biogas upgrading were:

- Small Scale ($<100 \text{ m}^3/\text{hr}_{\text{biogas}}$) = €c3-4/kWh of upgraded gas (app. 2.5-3.5p/kWh),
- Large Scale ($200\text{-}300 \text{ m}^3/\text{hr}_{\text{biogas}}$) = €c1-1.5 /kWh of upgraded gas (app.0.85-1.3p/kWh).

Although these were the operational costs, the total investment costs were reported to be around £1,300/m³/hr of biogas entering the upgrade system (Persson et al. 2006). Assuming a biogas quality of 60% CH₄, this was calculated to be equivalent to £216/kW of upgraded biogas. The correlation from Jönsson (2004) showed that this was linear for up to 1,200 m³/hr of raw biogas. Thereafter the initial investment costs per cubic metre per hour decreased exponentially to as low as £8/kW. The latter was for a large AD plant, capable of outputting over 1,500m³/hr of biogas. As a result the correlation from Jönsson (2004) was used.

The data used for the calculations above was based on research carried out in Sweden on 16 commercially operational biogas-upgrading plants. To model the use of biogas upgrading for the South West of England, ideally an example from the UK should have been analysed. At the time of writing there were no commercially available biogas upgrading plants for vehicle fuel in the UK.

9.5 Revenue analysis of biogas use

Having examined the production and biogas preparation costs, the financial returns of biogas were subsequently analysed. This section examines the revenue generated by the three main uses for biogas: electricity, heat production and upgrading biogas for transport. In addition to this, the analysis also examined the potential revenue from supplying natural fertiliser from the by-product of the AD process.

9.5.1 Revenue from electricity production

Renewable Obligation Certificates (ROC) can supplement the production of electricity from biogas. Following a series of consultations during the period 2007-2009, the UK Government banded the financial support mechanisms for renewable electricity depending on the conversion technique used (BERR 2008d; DTI 2006; DTI 2007). The banded ROC scheme was introduced in April 2009 (BERR 2008d). The aim of the banding was to increase the deployment of less established and commercially uncertain schemes. Schemes with established costs were awarded less ROCs per unit energy output, whilst emerging and pilot-scale conversion technologies were awarded more. The banding favoured bioenergy conversion processes, however the funding mechanism only favoured electricity generation.

As shown in Table 9-2, bioenergy conversion processes such as gasification, AD and pyrolysis all receive double ROCs. A typical buy-out value of a ROC at the time of writing is £37.19/MWh (Ofgem 2009). The double ROC proposed for AD makes it significantly more economically attractive. However this could ultimately reduce the diversity of the biogas fuel due to the economic payback offered for electricity generation over heat or transport fuel.

Band	Technology	Support Level ROC/MWh
Established 1	Landfill gas	0.25
Established 2	Sewage gas, co-firing on non-energy crops	0.5
Reference	Onshore wind, hydro-electric co-firing of energy crops, energy from waste with CHP	1.0
Post-Demonstration	Offshore wind, dedicated regular biomass	1.5
Emerging	Wave, tidal stream, fuels created using an advance conversion technology (anaerobic digestion, gasification and pyrolysis), dedicated biomass burning energy crops (with or without CHP), and solar photovoltaic, geothermal, tidal impoundment.	2.0

Table 9-2 Overview of ROC banding - Adapted from BERR (2008c)

The ROC is also supplemented by the standard selling price of electricity which is obtained regardless of the electricity generation technology. The cost of this will vary depending on the amount of kWh produced and the purchaser of the electricity. The average buying price for a single kWh of electricity is between 4-5p/kWh (Eco Centre 2009). The average cost of a ROC/kWh is between 3-4p/kWh (*ibid*). In Germany renewable electricity is rewarded through different mechanisms compared to the ROC schemes in the UK. The German financial support mechanism in place uses feed-in tariffs (FIT). The tariff is dependant on the type of conversion process used and more importantly the scale of the plant. The rate is also guaranteed for 20 years (Stern 2007). This technique is less uncertain than the ROC scheme currently present in the UK as it secures at least 20 years of funding.

The feed in tariff guarantees a payment per unit of electricity produced for a number of years (as long the producers continue to produce the electricity). These tariffs vary according to plant size and in the case of AD vary depending on the feedstock used for biogas production. A table has been reproduced from Yeatman (2005) to show the difference in feed in tariffs based on these dependencies; this is shown in Table 9-3.

Power Output	Tariff €/kWh	Bonus (€) based on using manure or energy crops
0-150 kW	11.5	6
150-500 kW	9.9	6
500-5000 kW	8.9	4
>5000 kW	8.4	4

Table 9-3 Feed in tariffs for renewable electricity from biogas in Germany (Yeatman 2005)

The use of feed in tariffs has also been recently introduced for the UK electricity market following the release of the Renewable Energy Strategy for the UK (HM Government 2009). According to the latest strategy, these tariffs are intended to incentivise small-scale renewable technologies. The scheme is designed for electricity generating capacities between 50 kW up to 5 MW. Electricity producers using systems under 50kW are only eligible for feed-in tariffs (FIT); whilst between 50kW-5MW have the choice between FIT and ROC. Systems above 5MW are only eligible for ROC funding (Ofgem 2010).

The use of feed in tariffs (also commonly known as FIT within UK Government literature) is more widely used across Europe than any other support scheme for renewable electricity. Of the 27 EU member states, 70% operate using FIT (Brown et al. 2009). Although FIT appears to be an attractive proposition for the UK energy sector and one which has been vocally favoured over a number of years, there are risks and uncertainties associated with this policy support scheme. The issue of a fixed price over a number of years could result in a deceleration of technology development and efficiency improvement, as financial income is secured. However an argument against this is that an increase in electrical output would yield an overall higher financial return, therefore the drive for efficiency would still be present. The development of alternative technologies however may be affected if one single technology proved to be financially viable.

Calculating the financial returns from renewable energy technologies can be rather complex as it is dependant on the technology, the end-use and the scale of production. Attempts have been made by the Energy Saving Trust to simplify the methodology for searching for electricity purchasers by launching an online buy-back tariff search engine (Energy Saving Trust 2009). However, this is limited to small-scale generating plants only. Literature sources use a typical electricity selling price from biogas of around 7.5-10.25 p/kWh (Yeatman 2005). Other sources, have estimated the price of electricity to be around 15 p/kWh (Redman 2008). FIT rates for AD are divided into two categories. These are large scale (>500kW) and small scale (<500kW). The FIT rates for these are 11.5p/kWh and 9p/kWh respectively (DECC 2010a). For the purpose of this study, a range of electricity selling prices were used to account for the lowest return and the maximum possible return using the financial support mechanisms available.

9.5.2 Revenue from biogas as heat energy

There is an aim that 12% of the UK's total heat requirements will be derived from renewable resources, such as biogas (HM Government 2009). Biogas could have a leading role in supplying localised or district heating in the future. Although heat energy is not incentivised

by additional financial support, considerations into the use of financial support for heat have been addressed by the Government and are expected to materialise within the following years (BERR 2008b). This has progressed further through a consultation of the Renewable Heat Incentives (RHI) during the first quarter of 2010 (DECC 2010b). This is proposed to be 5.5p/kWh of heat produced, whilst cleaned biogas injected into the grid would be eligible for 4p/kWh (DECC 2010b). These rates of return are amongst the lowest of all renewable heat production systems.

Analysing data from operating AD plants showed that heat energy in Germany was rewarded financially under certain circumstances. These included plants that were solely fed by either manures or energy crops. The cost of renewable heat in these cases was found to be between 4-6 €/kWh (3-5p/kWh equivalent) depending on the plant scale. The percentage of the income derived from heat was found to vary between 3-26% of total annual revenue. The majority of the income was associated with the electricity production. For the purpose of this study, the financial investment appraisal carried out on the case studies assumed a financial return from displacing the use of kerosene only. This was considered to be more realistic as the RHI had yet to be finalised.

9.5.3 Revenue from biogas as transport fuel

Some bioenergy fuels used as a transportation fuel are eligible for 20 pence per litre (ppl) discount on fuel excise duty, resulting in a duty of 30.35 ppl (Nix 2009). Excise duty for biogas and natural gas is 19.3p/kg of gas (HM Treasury 2009), whilst biodiesel for non-road use is eligible for a fuel duty of 9.69ppl (*ibid*). In addition to this, the implementation of the renewable transport fuel obligation (RTFO) obliged companies who supply in excess of 0.5 million litres of fuel per year to incorporate at least 3.25% by volume of fuel from renewable sources. Failure to comply with this obligation would result in a 'buy-out' of 15ppl (Nix 2009).

The energy content of LPG was found to be between 45-47 MJ/kg (Milukas, V 1993; Yan & Crookes 2009), whilst the energy content for liquefied natural gas LNG (equivalent to upgraded biogas) was around 43 MJ/kg. Estimated revenue per cubic metre of biogas used in the NNFCC economic model for UK biogas production (Redman 2008) was around 55 p/m³; using an excise duty value of around 10ppl. With the updated excise duty, the new correct revenue per cubic metre of biogas (assuming a methane quality of 58%) was calculated to be 45.3 p/m³. This value was used within the subsequent analyses.

9.5.4 Revenue from digestate as an artificial fertiliser replacement

The financial value of digestate as a valuable fertiliser varied significantly throughout the literature. A study carried out by Chesshire & Ferry (2006) calculated a value of digestate compared with the application of slurry and inorganic fertiliser that would have been applied to the field if there was no AD facility. This value was around £1.17/tonne of digestate. This value only represented the difference in nitrogen, potassium and phosphate composition (N, P₂O₅, K₂O respectively) between the digestate and standard fertiliser techniques.

Other literature sources showed a financial value of £4-5/tonne of digestate based on UK costs of N, P₂O₅ and K₂O (Redman 2008). This figure was cross-referenced against typical mineral fertiliser prices (Nix 2009). The calculation carried out and used in this thesis used the N, P₂O₅

and K₂O contents in dairy cattle manure and applied to current fertiliser base prices from literature (Nix 2009). Using this technique, a mineral-based fertiliser displacement value of around £10/tonne was calculated. This highlighted a large difference between literature sources. Other sources suggested a fertiliser selling price of €40/tonne (£36/tonne) used for an economic assessment of biogas production in Ireland (Murphy & Power 2009). As a result a sensitivity analysis was undertaken, which covered a range of the fertiliser values. A base value of £4.5/tonne was selected as this was inline with one of the most current sources (Redman 2008).

9.6 Assessing the financial appraisal of AD

A number of factors can affect the financial performance of an AD plant. These factors include the operation, scale, and end-use of the biogas from an AD plant. In many situations referred to in literature, the economics of using AD have generally resulted in favourable outcomes (Ecofys 2005; Murphy & Power 2009).

Having examined the techniques for determining the financial investment appraisal (FIA) of renewable energy options in general it can be seen that a number of assumptions affect FIA. Findings from Slesser & Lewis (1979) stated that this type of assessment is greatly affected by: the discount rate chosen, the rate of energy price increase (electricity, heat or transport fuel) and the expected life of the plant. When considering AD there are also other considerations which affect an economic assessment; these include:

1. Cost of fertiliser
2. The type of feedstock chosen
3. The availability of grants and external funding for initial capital outlay - resulting in the possibility of interests on loans.
4. The operational and maintenance costs associated with the plant (affected by the plant downtime also).
5. The use for the biogas

To understand how these considerations impact the financial aspects of an AD operation, a series of financial investment appraisals were carried out on existing AD plants. The assessment was carried out by creating a financial model for two plant case studies (plant A and plant C). The models used a 20 year period for discounting inline with the expected plant lifetime.

9.7 Results - financial appraisal of a small-scale AD plant

A financial appraisal was carried out on plant A, a small-scale AD plant in the UK. The results have been displayed in Table 9-4 and show a range of scenarios, from high financial return and low costs, to low return with high costs. None of the three scenarios paid back over the life of the plant due to encountering a financial loss each year of operation.

The AD plant used in the case study (plant A) was recorded to consume 2,806 kWh of electricity supply. Assuming a cost of electrical supply for a small-scale non-domestic unit of around 8-12p/kWh (DECC 2008) and a fixed cost of 30-40p/day, the electrical energy consumption per year for the plant was calculated to be between £335-480/annum.

Plant A (UK AD Plant)			
Plant Output (biogas/tonne of feedstock)	17.1	m ³ /tonne of feedstock	
Annual biogas output	11,166	m ³ /year	
Biogas used for heating (Appendix B)	3,526	m ³ /year	
Annual Revenue	Low return	Medium return	High return
Heat (via cost of displaced kerosene)	£888	£1,012	£1,234
Fertiliser (assuming dairy cattle manure)	£1,306	£2,939	£6,530
TOTAL (per annum)	£2,194	£3,950	£7,764
Annual Costs			
Electricity	£483	£408	£334
Heat	£750	£615	£540
Maintenance	£10,375	£8,152	£5,929
Financial costs (5% APR over 20 years)	£24,097	£14,432	£5,947
TOTAL (per annum)	£35,705	£23,607	£12,750
Annual Profit/Loss	-£33,511	-£19,657	-£4,986
Capital Investment	£300,300	£179,852	£74,110
Simple payback period	No Payback	No Payback	No Payback
Total present value costs (PV)	£844,964	£694,199	£558,888
Net Present Value (NPV)	-£817,616	-£644,969	-£462,133
Benefit Cost Ratio (BC)	£0.03	£0.07	£0.17

Table 9-4 Financial investment appraisal of small-scale AD plant in the UK (plant A)

The results show a similar outcome to the energy analysis of the small-scale AD plant. The plant does not perform financially. The plant's very low capacity factor (14%) means that it only operates at just over a tenth of its potential. This is due to the lack of feedstock availability. Secondly, the biogas output per tonne of input is lower than average values of biogas from dairy manure.

One of the most significant factors affecting the plant's financial performance is the end-use of the biogas. The biogas plant produces more biogas than is required for the nearby property where the biogas is used for heating. As a result, excess biogas is burnt off in the digester to heat the feedstock to a higher operating temperature. Not all of the biogas is used to obtain financial reward, as the demand is very low. Additionally, the cost of displacing kerosene as a fuel (i.e. using biogas for heating) is the least financially profitable biogas use, when compared to electricity production and transport fuel.

9.8 Results - financial appraisal of large-scale AD plant

The AD plant examined in Chapter 7 was denoted as plant C. Based on the energy analysis results, this plant is considered as a potentially attractive proposition for implementation in the South West of England.

The operational data used for this financial appraisal included a daily biogas yield of 3077 m³/day, an input quantity of 92.6 m³ per day (equating to 33,812 m³ per year) and a feedstock composition of over 90% dairy cattle manure. Other feedstocks included the use of 220ha per year of maize silage, equating to around 2,650 tonnes of silage per year. The cost of this feedstock was known and therefore remains constant throughout the analysis.

The analysis was carried out using the findings and assumptions stated throughout the previous sections. The investigation was then further extended by comparing the end-use biogas for either electricity production or as transport fuel. The results have been tabulated in Table 9-5 below showing the extremities between the 'High return' and 'Low return' scenarios. These two boundaries used the full range of obtained data for all of the costs and revenues affected by the plant.

<i>Annual Revenue</i>	Combined Heat and Power		Transport Fuel	
	High Return	Low Return	High Return	Low Return
Electricity	£331,736	£143,752	-	-
Heat	£103,060	£90,492	-	-
Transport fuel	-	-	£527,859	£426,780
Fertiliser (assuming dairy cattle manure)	£152,096	£50,699	£152,096	£50,699
TOTAL (per annum)	£586,891	£284,943	£679,955	£477,478
<i>Annual Costs</i>				
Electricity	£1,839	£4,904	£1,839	£4,904
Heat	£243	£280	£54,060	£61,233
Maintenance	£32,001	£129,234	£32,001	£129,234
Other production costs	-	-	£49,641	£87,602
Financial costs (5% APR over 20 years)	£32,098	£74,072	£19,732	£78,496
Crop expenses (based on 200ha of maize)	£73,514	£73,515	£73,516	£73,517
TOTAL (per annum)	£139,694	£282,005	£230,789	£434,986
<i>Annual Profit/Loss</i>	<i>£447,197</i>	<i>£2,937</i>	<i>£449,166</i>	<i>£42,493</i>
Capital Investment	£400,010	£923,100	£245,904	£978,230
Financial payback period	0.89	314.25	0.55	23.02
Total present value costs (PV)	£2,126,854	£4,386,846	£3,070,191	£6,292,440
Net Present Value (NPV)	£6,219,412	-£1,963,562	£5,403,550	-£342,003
Benefit Cost Ratio (BC)	3.92	0.55	2.76	0.95

Table 9-5 Financial appraisal for large scale AD plant (plant C)

The results of the analysis suggest there could be a considerable difference between high and low range results when assessing the range of costing and revenues for AD. Taking electricity production for example, the payback time for the plant could either be around 9/10 of a year

or, considerably more. It is therefore evident that the assumptions made when carrying out an FIA for AD plants are extremely critical to the outcome. Having said this, the all-positive outcome is a reassurance that AD of this scale and setup could be financially feasible.

Furthermore, it emerged that the use of biogas as a transport fuel could be financially more attractive than combusting the gas for electricity generation. This estimation was made assuming that biogas upgrade facilities were for large scale only (therefore assuming a cost of upgrading between 0.85-1.3p/kWh of upgraded biogas). The implications of this were also considered within the sensitivity analysis.

The analysis also assumed that the capital investment was supplied on a loan basis with a 5% APR over 20 years, inline with similar studies (Murphy & Power 2009). The capital investment figures took into account whether a CHP unit would be required or whether the biogas upgrade unit was used. Realistically, when developing a plant of this scale, it would be beneficial to apply for support mechanisms available from the Government in order to ease the burden of setup costs.

In order to calculate the PV and NPV a discount factor (DF) of 5% was used. The current test discount rate (TDR) employed by the UK Government for investment appraisals is 3.5% (Allen et al. 2008a). If an investment has a high uncertainty, then a higher discount rate is used as the investor wishes to recuperate the invested capital quickly. Some studies of renewable energy projects have carried out investment appraisal with a 0% discount rate (Butcher et al. 2006). Due to the uncertainties of AD in the UK a discount rate of 5% was chosen. This was considered adequate and represented the TDR between 2003 to present (where in 2003 the TDR was 6%). Although a sensitivity analysis on the discount rate was not carried out, a higher discount rate would have decreased the NPV of the plant, whilst a lower discount rate would have increased the NPV.

The analysis showed that three of the four scenarios for plant B paid back within an assumed plant lifetime of 20 years. The 'worst case' electricity production setup did not payback and had an NPV of -£2million. The possible reason for this was the lower selling price of electricity used (7.5 p/kWh). This price was considered the lowest possible selling price for electricity. The displacement of kerosene fuel for heating also affected the low return on investment, assuming a low kerosene price of 36pppl. Although this analysis showed a negative payback at these prices, other studies have suggested that AD plants could operate at these selling prices (Yeatman 2005). The use of biogas for road transport proved to be almost financially viable for both scenarios. Although there were additional operating costs associated with this technology, the revenue for selling the biogas provided a benefit-cost ratio ranging from 0.95 to 2.76.

9.9 Sensitivity analysis of financial investment appraisal

9.9.1 Cost of selling electricity

The electricity selling price was a factor with a considerable percentage uncertainty. The price was varied to account for single and double ROC schemes and the recently implemented FIT scheme. The cost of selling electricity varied considerably within literature, especially for large-scale installations. For a fixed methane quality, the change between 7.5p/kWh to 15p/kWh showed a change in revenue of over £150,000 for the plant. This variation accounted for the range of selling prices which electricity from biogas could reach with the different support mechanisms. This has been shown in Figure 9-2. Literature suggested that a single ROC scheme system would equate to a selling price of 7-11 p/kWh, whilst a double ROC scheme could increase to 10-15 p/kWh. The FIT scheme varied between 9-11p/kWh and therefore was within this range.

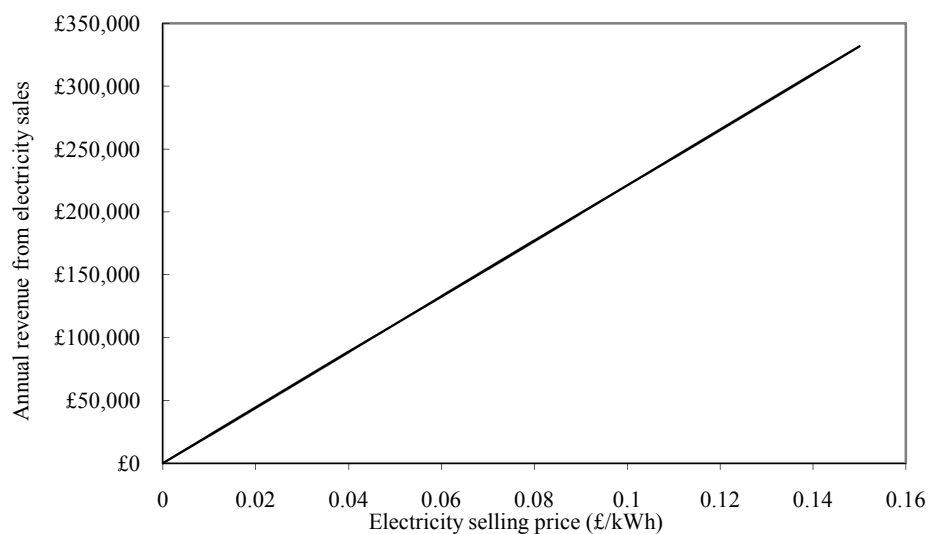


Figure 9-2 Sensitivity analysis of electricity selling price on revenue from electricity sales

Another significant factor affecting the revenue from exporting electricity was found to be the methane quality of the biogas produced. The methane quality within the analysis was limited to between 52-60% however, in other plants this can vary from 50-70%.

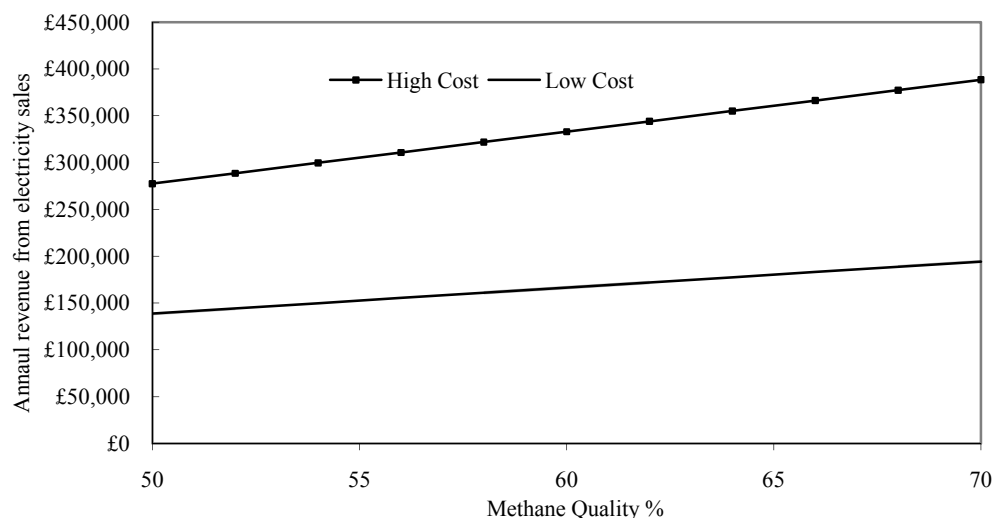


Figure 9-3 Sensitivity analysis of changing methane quality between 50-70%

A sensitivity analysis was carried out for this and showed that for a high buying cost the methane quality could have an affect of over £100,000; equivalent to 30-40% of the total revenue from electricity sales. This has been shown in Figure 9-3.

9.9.2 Transport fuel

Selling biogas as a transport fuel assumed a fuel excise duty of 19.3ppl. It also assumed a methane quality of 58% and a cost of fuel displacement of 110 ppl. As vehicle fuel prices vary significantly, a range between 85-120ppl was used to show the impact of this on the financial return of biogas. This change resulted in a differential of just under £200,000, equivalent to 17 p/m³ of biogas, as shown in Figure 9-4.

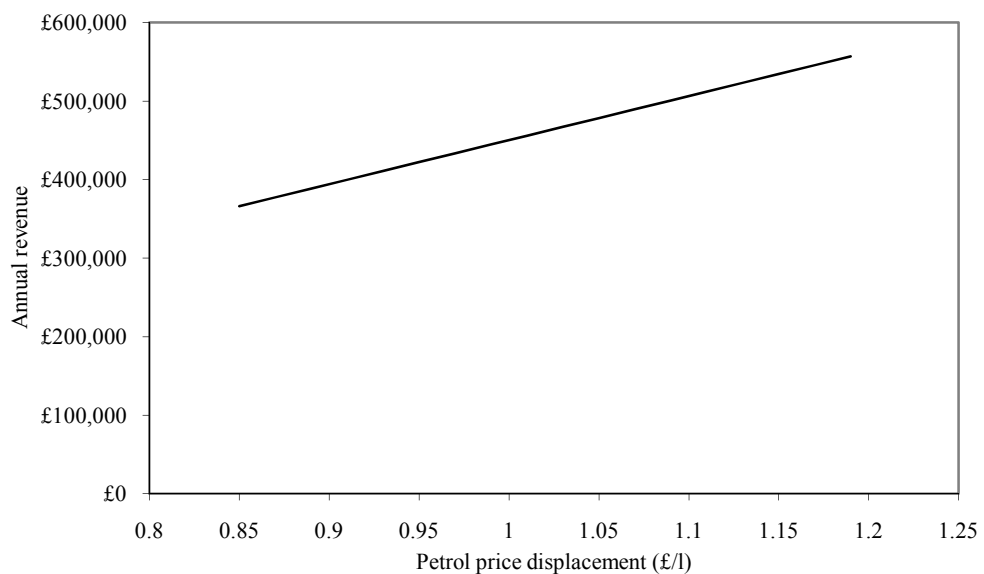


Figure 9-4 Sensitivity analysis of biogas for transport revenue based on fossil fuel price change

9.9.3 Fertiliser selling price

The cost of purchasing fertiliser is dependant on a number of factors. These include the primary composition of sellable nutrients (N, P₂O₅ and K₂O). The price of the nutrients can also vary substantially, as shown in Appendix B where over the recent years the cost of fertiliser has significantly increased. The current value for cattle manure digestate was assumed to be around £4.5/tonne. For digestate from energy crops this can rise to up to £40/tonne (£35/tonne) depending on the quality (Murphy & Power 2009).

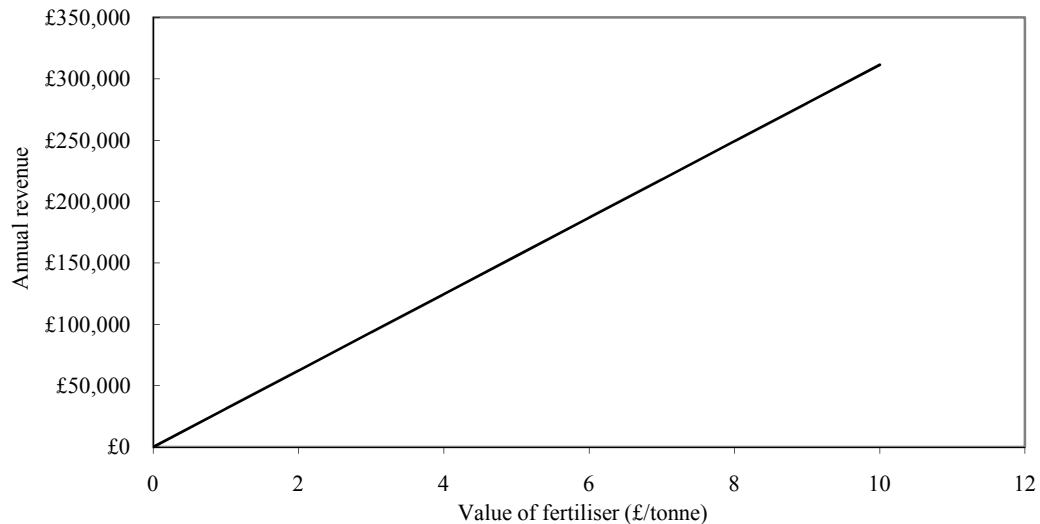


Figure 9-5 Sensitivity analysis of revenue from fertiliser

Data obtained from German AD plants showed that the selling price of fertiliser from digestate was significantly lower than theoretical prices quoted in UK AD scenarios (FNR 2005). The actual selling price ranged between £0.2-0.5/tonne of fertiliser. The cost of fertiliser in Germany may differ from the UK and therefore should not be used within the sensitivity analysis. A sensitivity analysis for a fertiliser price range between £2-£10/tonne was carried out, as these were the extremities found for digestate fertiliser values in England. In addition to this, the analysis only considered the annual digestate derived from cattle manure, therefore deducting the digestate from silage. As shown in Figure 9-5, the change in fertiliser price by £10/tonne showed a change in annual revenue of £300,000.

9.10 Additional financial drivers for bioenergy pathways

All bioenergy types must be financially appealing, both at production and use phase, in order for them to have an increase in implementation (Adams et al. 2008). Within the bioenergy supply chain, feedstock suppliers and conversion process operators view this driver as the primary objective for a successful bioenergy plant.

To support the implementation of AD in the UK, there are a number of financial support mechanisms. The financial support for bioenergy within the UK is distributed across the bioenergy supply chain. One of the most established mechanisms is the Energy Aid Payment. This payment funds growers by around €45/ha to grow crops for heat, transport and electricity (Nix 2009). Growers in England can also apply for the Energy Crop Scheme managed by Natural England. This scheme offers an establishment grant for energy crops such as miscanthus and short rotation coppice (SRC). These payments can cover up to 40% of

the actual costs (suppliers, materials and contractors) and on-farm costs (machinery, labour, etc) (Natural England 2008). The final scheme available to suppliers of feedstock is called the Bio-Energy Infrastructure Scheme. This scheme helps develop the supply of energy crops through the setting up of producer groups to supply biomass to energy end-users. The scheme offers up to £200,000 per project.

Other direct financial support mechanisms specifically designed for the conversion of biomass to bioenergy include the Bio-energy Capital Grant Scheme which supports the development of CHP and power generation from biomass feedstocks. The fifth round of this scheme ended in July 2009 and it is anticipated that another round will commence within the following years. The scheme only supports the energy generation process and not the production of the feedstock. The scheme can cover costs of up to 40% to a maximum of £100,000 (Nix 2009).

Other financial drivers for bioenergy are regarded to be 'indirect'. Indirect financial drivers are possible economic benefits created through the implementation of legislations and regulations which do not directly apply to the bioenergy conversion process. An example of this is the Landfill Directive which aims to reduce the proportion of biodegradable waste entering a landfill. Through this directive and the Landfill Allowance Trading Scheme, a fixed penalty of £150/tonne is incurred if biodegradable materials enter a landfill over the permitted allowance. This is subsequently an indirect economic driver for energy from waste applications (DEFRA 2009a). Energy-from-waste plants can also charge a gate fee of over £30/tonne to uptake biodegradable waste, similar to the charge from landfill sites (DEFRA 2009b).

9.11 Summary

The study carried out a series of financial investment appraisals on two AD plant case studies. The analysis compared the use of small-scale vs. large-scale biogas production on a financial basis. The results re-affirmed the results from the energy analysis. Small-scale biogas production was affected by the low feedstock uptake and the low conversion efficiency of the feedstock (low biogas yield per tonne of input). These factors, which had a negative impact on the energy analysis, also had a disadvantageous effect on the financial appraisal. The scale of the plant also resulted in a limited biogas use (heating only).

The large-scale AD plant showed relatively positive financial benefits if both heat and electrical power were given a financial value. Biogas used for electricity alone was found to increase the financial payback of the large-scale AD plant significantly. The study then analysed the potential of biogas production as a transport fuel. Based on current operational costs of biogas conversion to transport fuel, the financial appraisal results showed an improvement over the use of biogas for heat and electrical power.

The implications of the financial investment appraisal have been addressed in Chapter 10. The chapter also discusses how the current financial market affects the performance of biogas production. Finally, it provides recommendations and conclusions based on the outcomes of the financial modelling.

10 INTERPRETATION AND DISCUSSION OF FINDINGS

10.1 *Introduction*

The thesis has identified the biomass resource availability in the South West of England, followed by an assessment of the barriers and drivers for bioenergy development. These two research areas allowed an appreciation of all types of biomass resources, bioenergy pathways and their implementation within the region and also within the UK.

Subsequent to the resource assessment, a multi appraisal technique was applied to a single bioenergy pathway: - biogas production from anaerobic digestion (AD). This pathway was chosen based on its performance within the resource assessment. The appraisal technique assessed the environmental impacts of AD performance based on energy analysis and an appraisal of the financial investment.

The implications of the results have been discussed in the following sections and highlight the impact of the data used, the methodology adopted and the significance of the results in a regional context.

10.2 *Biomass resource assessment for the South West of England*

The study highlighted the potential for bioenergy production in the South West, with the prospect to significantly increase its current uptake. The region's extensive agricultural sector and high generation of waste resources favoured the potential increase for bioenergy production.

Results from resource assessment C (see Figure 3-10) showed the maximum contribution from biomass sources in the South West could be just under 54 PJ_{NCV} of energy per year. Energy crops from the previously available set-aside land and other permanent grassland were found to contribute up to 9 PJ_{NCV} per year. This correlates to similar findings in previous resource assessments for the South West (Scholes 1998) in which calculations for bioenergy from energy crops revealed a minimum potential contribution of just under 3,000 GWh (10.8 PJ_{NCV}). However this study has examined bioenergy as a whole rather than focusing solely on one type of feedstock.

It is apparent that for significant development in bioenergy, by-product feedstocks such as organic domestic, industrial waste and waste from farming could contribute significantly towards the region's biomass mix. Nevertheless, all feedstocks should be considered further as they could provide a more sustainable solution for energy production. The adaptability of biomass feedstock allows the adoption of multiple conversion techniques for bioenergy. This may be more beneficial than creating a mono-conversion system for bioenergy in the region. This would eliminate one of the key benefits and drivers for biomass use, i.e. its diversity.

In 2001, the South West reportedly consumed 547.2 PJ_{NCV} of energy from domestic, industrial and service sectors (Chambers et al. 2005). Resource flow scenarios for 2015 predicted energy consumption would rise to 573 PJ_{NCV} if no energy efficiency measures were considered (Chambers et al. 2005). Correlating the trend to 2020, would suggest an estimated energy consumption of 599 PJ_{NCV}. Adopting Resource Assessment C would suggest that bioenergy

could contribute 6% to 9% of the total energy use in the region. Additionally, the study also highlighted the potential of currently available biomass within the region (resource assessment B, Figure 3-9). Currently available feedstocks for bioenergy were shown to be within a similar range as those calculated in assessment C. Both of these resource assessments did highlight a significant potential increase in bioenergy compared to the levels currently produced in the South West (resource assessment A). This was significant as it showed that the bioenergy potential within the region is not being exploited.

The South West's main sector for energy use is currently domestic, comprising of nearly 50% of the region's energy mix (Chambers et al. 2005). The highest contributor towards this demand was the energy requirement for space heating (*ibid*). Bioenergy could offer a significant contribution towards meeting some of this demand. This could be an efficient use of the biomass resource which would also eliminate the requirement for expensive or technologically challenging bioenergy conversion techniques (heat from biomass requires relatively simple conversion techniques). Table 10-1 shows how the bioenergy potential calculated in resource assessment B could contribute towards each of the three main energy consumption sectors for the South West of England.

Primary energy consumption by sector	Energy Consumption for 2001	Potential bioenergy contribution adopting resource assessment B	
	PJ	Minimum	Maximum
Domestic energy consumption	258.3	10%	20%
Industry energy consumption	89.7	30%	55%
Services energy consumption	198.4	14%	25%

Table 10-1 Potential bioenergy contribution towards South West energy mix, using resource assessment B

If used solely for the domestic sector, bioenergy could contribute towards 10-20% of the region's energy, whilst for the industry sector alone this could be between 30-55%. The diversity of bioenergy would undoubtedly result in a mix-contribution towards all three energy-use sectors as opposed to accounting solely for one. A foreseeable concern could arise if a particular bioenergy route were to become more profitable than the rest. This could result in a single or limited use for bioenergy determined primarily by economic return on investment. The environmental issues of adopting monocultures of biomass feedstocks could also have a negative impact on the region.

10.2.1 Implications of the resource assessments

The key findings from the three resource assessments in Chapter 3 showed that the current production of bioenergy within the region is extremely limited. However if measures were taken, the uptake of resources used for bioenergy could be significantly higher. The significance of this is that currently bioenergy is not being exploited within region. These findings can be linked with the findings from Chapter 4, where economic barriers to bioenergy feedstock suppliers proved to be a critical factor when considering the increase in bioenergy uptake. As a result these findings signify that there is no strong motivation or market attractiveness for bioenergy feedstock supply. The potential for bioenergy is clearly visible within the region, as the results from resource assessment B and C suggest. However the uptake of this resource will remain limited until new market drivers are introduced.

Another reason for this low resource utilisation could be the lack of conversion technologies available within the region (or the UK as a whole). The research from Chapter 4 highlighted a number of failed bioenergy plant attempts, which therefore limited the requirement of bioenergy feedstocks. The results suggest that a greater demand for biomass as an energy source would be needed to increase the bioenergy resource utilisation within the region. This could be brought about through increased Government support during the installation of conversion technologies or by establishing secure bioenergy supply chains within the region (such as AD for biogas production). Further financial incentives or possible financial reassurances (such as a secured grant) may also stimulate the bioenergy feedstock production market, minimising the risks of investment.

10.2.2 Implications of barriers for bioenergy development in the South West

The study carried out in Chapter 4 highlighted the strength and interdependence of the supply chain for bioenergy. The link between feedstock availability and supply and the adoption of the correct conversion technology is extremely relevant in developing a successful bioenergy project. However the demand for the end-use energy must be present in order to validate the use of the conversion technology. The support from policy and Government legislation can assist all three aspects of the bioenergy supply chain.

The study found that although similarities in barriers and drivers existed amongst the stakeholder groups representing the bioenergy supply chain, some aspects were unique to individual groups. For feedstock suppliers for example the key barrier to the development of bioenergy was found to be the uncertainty on investment. This is particularly true for feedstock suppliers of SRC or miscanthus, where annual returns are not possible due to the long growing periods of the crops. The uncertainty of demand for bioenergy feedstock inevitably leads to feedstock suppliers feeling insecure about investing in bioenergy. Financial aspects of bioenergy were also viewed as a key barrier for primary end-users of bioenergy. High buying costs of bioenergy feedstocks with respect to fossil fuels would ultimately lead to a reduced demand for bioenergy.

The barriers identified as most critical amongst conversion technology owners/developers were perhaps the most interesting and significant within the study. Technological uncertainties and limitations of the conversion technologies were seen as a critical barrier for developers/owners or investors. This barrier is highlighted significantly within case studies shown in Chapter 4, regarding the failed bioenergy developments. Uncertainties regarding the conversion technology could lead to increased investment, operational and maintenance costs. This would subsequently create indirect financial barriers for this stakeholder group.

However, perhaps more significant are the perceptual challenges felt towards uncertain or complex conversion technologies of biomass. The study acknowledged that due to limited public understanding, bioenergy plants were often associated with waste incineration systems which provided questionable benefits to the environment and the local community. This would undoubtedly reduce the willingness for local communities to accept a bioenergy plant installation in close proximity; particularly if the potential benefits are not transposed directly on to the community itself.

If the benefits and outcomes of adopting a bioenergy conversion technology were made clear, perhaps bioenergy projects within the South West may have been more successful. Bioenergy projects have a unique capability of being integrated within a local community. This could be a result of obtaining local feedstock, employing locally and using the energy within the proximity either through district heating or off-grid electricity production. Often however, biomass projects are of large scale, sourcing feedstocks from vast radiuses, which could offer limited employment opportunities locally due to the high skill/experience requirements.

The final part of the study in Chapter 4 confirmed the overarching influence which the Government can have across the whole bioenergy supply chain. The cluster of common barriers for this stakeholder group included the lack of resource availability, the potential rise in food prices and the use of unproven technology. These can clearly be related to the requirement of the UK Government to increase fuel security and deliver clean and affordable energy (BERR 2007a). The use of unproven technologies could lead to large Government investments with limited or very low returns. Although there are a number of Government funded schemes to aid financial investment into bioenergy technologies, the risk of the investment should be minimised. Financing significant portions of the bioenergy-capital-grant-scheme in unproven emerging technologies could provide a large uncertainty of return and reduce the possibility of funding for projects with more established technologies.

Government support through direct commercial funding, financing research and development or implementing support mechanisms at end-user energy levels (such as the ROC, feed-in-tariff etc) is present across the whole supply chain. Inevitably this support does not cover all aspects of bioenergy due to the vast number of pathways which bioenergy can take. For example, Chapter 9 highlighted the recent financial incentives for electricity and heat production from bioenergy. This is assisted further through the bioenergy capital grant scheme being eligible only for electricity and CHP systems. However, the use of bioenergy as a transport fuel does not have similar direct financial benefits. This consequently favours particular bioenergy pathways over others.

In the case of biogas production from AD, the use of farm manure as a feedstock can also be seen as an example of where financial incentives are lacking for particular bioenergy feedstocks. This highlights the disparity of how the Government assists particular feedstocks using financial aid yet fails to support others. Dedicated energy crops, as highlighted in the thesis, are eligible for a number of financial support mechanisms whilst farm manure used in favour of industrial waste is not financially rewarded (as was shown to be the case in Germany, Table 9-3). A potential recommendation is the possible introduction of financial reward systems of energy (electricity, heat and transport fuel) which take into account the whole supply chain of the bioenergy pathway. This would include the feedstock source and location, the conversion technology adopted and the energy end-use. In Germany for example, electricity producing AD plants which are fed from animal manure are eligible for additional government financial support. This could be implemented in the UK, thus rewarding the whole supply chain rather than limiting support to particular areas.

10.2.3 The significance of farm waste for the South West of England

The resource assessment highlighted the significant abundance of farm waste in the South West. Biogas production from farm waste is considered a secondary biomass source,

signifying the original biomass feedstock will have been processed to make a different type of bioenergy (FAO 2004). The benefits which biogas was considered to have were as follows:

- Biogas is not processed for a particular end-use energy commodity, such as electricity generation, heat supply or transport use. Therefore making it a versatile fuel;
- The majority of the current energy-from-waste in the South West is collected through biogas production and is generally the most accepted form of waste-to-energy;
- The production of biogas from farm waste enables the waste to be used as a natural fertiliser, thus not influencing the current end-use of farm manure;
- Biogas is considered a renewable energy source and is defined as a primary fuel according to the Digest of UK Energy Statistics (BERR 2008a);
- Biomass materials with high moisture concentrations (MC) are suitable for biogas production and would not be suitable for direct combustion. Most organic wastes (such as farm waste) have a relatively high MC therefore biogas production from these sources would be favourable.

The assessment concluded that a significant portion of bioenergy could be derived from organic waste. Organic waste includes organic matter in municipal/industrial waste and agricultural organic waste. The results from the resource assessment showed the potential of this biomass type was the most abundant throughout the assessments within the region.

The potential of energy recovery however, should not affect existing practices and techniques of handling farm waste. Currently farm waste is distributed in four main ways: incineration; pasture range and paddock, where the waste is excreted directly onto pasture land; storage, either in liquid form or solid form and daily which is when the waste is dispersed onto the land within a month of collection (Mistry & Misselbrook 2005). The use of anaerobic digestion (AD) for biogas production could alter the ways in which farm waste is handled. Importantly however, farm waste used as a fertiliser substitute would not be affected by biogas production. The adaptability of biogas as an energy fuel can also be favourable for exploiting this bioenergy option within the region.

The results from the resource assessment suggest that the use of AD for biogas production could be used as a suitable conversion technology capable of utilising the available feedstock. The resource assessment has highlighted a bioenergy pathway which could be suitable for the region's energy production. However the impacts of this bioenergy pathway have been examined and as a result this technology has been used in the multi appraisal technique. Although the study has limited the research area to a single bioenergy pathway it has been essential to do so in order to compile an accurate and meaningful assessment.

10.3 The bioenergy pathway investigated – Anaerobic Digestion (AD)

The study found that there are a number of operational parameters which affect the performance of anaerobic digestion (AD) for biogas production. The complexity of the AD process signifies that there is often considerable instability. This instability is instigated by the drop in methane generation, drop in pH and an increase in surface scum (Lyberatos & Skiadas 1999). In the study carried out in Chapter 6 the operating parameters for a number of existing AD plants were analysed. It was shown that although the expected correlations existed, the

percentage error was too high for them to be used reliably in order to estimate the biogas potential for the South West. As a result detailed energy analyses were required for individually chosen AD plants, used as case studies.

Analysing the theory of kinetics for AD along with the operational data obtained from biogas producing plants showed broadly similar correlations. The methane yield of a digestion plant grows linearly with the increase in size of digester; this was clear from theoretical and actual plant data. This rise in methane with respect to digester size was found to be higher ($0.65 \text{ m}^3/\text{m}^3$ of digester) for mixed wastes (manures and co-substrates) than with a single manure feedstock ($0.55 \text{ m}^3/\text{m}^3$ of digester). In the case of mixed wastes, a rise in methane yield of around 15% was seen. However this could not be used as a basis for all biogas calculations of mixed feedstocks due to the variability of feedstock biogas yields; but simply to re-emphasize the link between digester size and expected methane yield per day. The significance of the results showed that the use of co-substrate addition could increase biogas yields without significantly increasing the plant size. This could be a consideration if AD were to be implemented in the South West of England.

The results also demonstrated the increase in methane yield per unit volume of feedstock in relation to the increase of volatile solids (VS) concentration. This was understood to be due to the VS concentration affecting the degradability of the material. Nonetheless, the reduction in methane yield as the VS concentration increased was not observed with the German operational plant data. This signified that the large variation in feedstock types used in the operational plants resulted in changes in total solids (TS) and volatile solids (VS), which ultimately had an effect on the overall biogas yield. Different hydraulic retention times (HRT) and variation in the use of single or multi-stage AD processes could also have affected the results. It was apparent that the main cluster of results showed AD plants operated between 5 and 15% VS, which subsequently meant the corresponding TS concentrations, were also around 5-15%. The findings implied that digester design should be focused on operating using an optimum VS concentration and similarly suitable TS concentration. A compromise should therefore be obtained between the maximum degradability of the feedstock for biogas production and the feedstock which requires the least energy demand during the digestion process.

The findings were significant as they highlighted that AD plants can operate on relatively low dry matter concentrations. This means that the majority of the feedstock should always be water in order to maintain the TS at appropriate levels. These findings would appear to strengthen the theory that AD for biogas tends to be more successful in wetter climates such as north Europe and North America. Geographical regions where water is more limited may not suit the use of AD.

Inhibitors which affect the performance of AD plants were found to be varied and generally unclear within literature. Although an efficiency parameter could be inversely linked to the VS concentration of a feedstock, it did not explain exactly why the parameter was affected. This was because there are a number of different inhibitors which are produced at varying stages of the process, depending on the setup of the AD plant. The most common type of inhibitor was understood to be ammonia, which is formed from the anaerobic degradation of nitrogen compounds (Deublein & Steinhauser 2008). Other inhibiting factors included organic acids. If

the rate at which these organic acids are fed into the digester is too high, the acidification stage of the process is expanded. This subsequently drops the pH value and increases the generation of acetic acids ultimately reducing the methanogenesis stage.

It was understood that the longer the digestion time (HRT) the more methane was captured per unit weight of feedstock. According to the model produced by Karim et al. (2007), the methane production rate is roughly inversely proportional to the HRT. This is because the process is allowed more time to recuperate the remaining available biogas. This understanding highlighted the requirement to find a compromise between the time to digest the material and the acceptable methane yield to be extracted. A longer digestion time could reduce the overall annual biogas output, in an effort to capture as much of the methane as possible.

The study enabled an understanding that the use of biogas from AD as an energy source is not solely affected by the conversion technology. The feedstock properties such as VS, TS and ultimate methane yield dictate a significant portion of the biogas capabilities of an AD plant. The implementation of an AD plant is therefore highly affected by the whole supply chain from feedstock production to biogas end-use.

10.4 Review of the multi appraisal technique for biogas

The assessment of a single bioenergy pathway for the South West of England was undertaken using a multi appraisal technique. The technique examined the net-energy performance, the financial capability and the environmental impacts of biogas production from AD.

The multi appraisal technique was applied in detail and specifically to three case studies. The significance of these case studies was to address a range of AD plant sizes, biogas uses and feedstock types. The plants were denoted as plant A, plant B and plant C. One of the three case studies was an installation within the study area (South West of England). A reminder of the plant description can be found in section 6.1.

Assessing the environmental implications of biogas production proved to be the most time and resource intensive of the three appraisal techniques. The validity of LCA was dependant on the quality of data collection and the detail of data available. Therefore, non-theoretical data was essential in carrying out an LCA. In order to carry out a valid and representative LCA, the methodology was carried out on a single AD plant (case study plant A). This was considered as a good representation of single-feedstock biogas production as emissions could easily be correlated to varying plant scales. The net-energy analysis and financial appraisal were comparatively more straightforward and therefore could be applied to a wider range of case studies.

10.5 Review of energy analysis

Energy analyses carried out for biogas production were found to vary extensively depending on the AD plant setup. Therefore, it was difficult and misrepresentative to compare the energy analysis in this study with those in the literature. These variations occurred within the system boundaries of the studies and the conversion efficiencies used for calculating the primary energy of fuels for electricity and heat.

The research was significant in showing how energy analysis could be used as a tool in examining the energy requirements of the whole product or process chain. Comparing the energy analysis results (ERE in particular) calculated for the three case studies used in Chapter 7, against published literature showed significant discrepancies. Previous analysis showed a typical ERE of 2.58 (Lewis 1977), which was then used and referenced in subsequent literature sources as a common representation of AD (Mortimer 1991). Closer investigation of the literature showed that the calculated biogas yield per unit input of cattle manure (the only feedstock selected by Lewis (1977)) resulted in approximately 1.1 m³ of biogas/m³ of waste feedstock. This is more than 20 times lower than quoted by some literature (Ecofys 2005) and significantly lower than any other related sources (Amon et al. 2007; Callaghan et al. 2002). The implications of this comparison meant that it is often difficult to create direct comparisons of AD plants as the biogas potential of the feedstock can differ significantly.

Other studies which carried out energy analyses of AD showed that for large scale electricity production biogas plants, an ERE between 0.6-2.4 MJ_{resource}/MJ_{delivered} was obtained (Berglund & Borjesson 2006). These results were consistent with the findings for the three case studies, highlighting the large variation in ERE depending on the efficiency of the conversion process. The ERE results obtained in Chapter 7 have been compared against a number of other energy sources, shown in Table 10-2. The output biogas has been modelled to either produce electricity, heat or a methane transport fuel.

The results shown in Table 10-2 indicate that electricity production from biogas has a lower ERE than currently utilised fossil fuel resources. However compared to other renewable sources such as hydro and wind, the ERE performs less well. Biogas for heating is also shown to have a slightly higher ERE compared to naturally combusting biomass sources. However, the thermal quality benefits of biogas, in that it is able to combust at much higher temperatures than solid wood for example, is not shown through the ERE calculations. As a result, the ERE may not fully represent the energy potential of biogas. In this case, the quality of the energy (exergy) for the system could subsequently be analysed. This could be considered as further research based on the outcome of the results obtained.

<u>Electricity</u>	MJ_{resource}/MJ_{delivered}	
Biogas Plant A	-	Based on 33% conversion efficiency
Biogas Plant B	1.42	Based on 33% conversion efficiency
Biogas Plant C	0.88	Based on 33% conversion efficiency
Wood fired Power Plant	0.82	(Mortimer 1991)
Hydro	0.01	(Allen et al. 2008b)
Large Scale Wind	0.05	2 MW – 30% capacity factor (Allen et al. 2008b)
Small Scale Wind	0.05	800 kW – 20% capacity factor (Allen et al. 2008b)
Solar	0.34	(Allen et al. 2008b)
<u>Heat</u>		
Biogas Plant A	1.66	Based on heating efficiency from SEDBUK (2009)
Biogas Plant B*	0.52	Based on heating efficiency from SEDBUK (2009)
Biogas Plant C*	0.70	Based on heating efficiency from SEDBUK (2009)
Biomass - Pine	0.02	30-90 yr. rotation (Mortimer 1991)
Biomass - Poplar	0.37	10 yr. rotation (Mortimer 1991)
<u>Transport Fuel</u>		
Biogas Plant A*	1.25	Fuel upgrade based on Borjesson & Berglund (2006)
Biogas Plant B*	0.50	Fuel upgrade based on Borjesson & Berglund (2006)
Biogas Plant C*	0.49	Fuel upgrade based on Borjesson & Berglund (2006)
US Ethanol	0.73	(Dale 2007)
Biodiesel from Jatropha	0.70	(Prueksakorn & Gheewala 2008)
Ethanol - Fermentation of Maize	2.03	Fermentation type (Mortimer 1991)
Ethanol - Fermentation of Straw	5.26	Fermentation type (Mortimer 1991)
<i>Petrol</i>	1.29	(Spielman et al. 2007a)
<i>Diesel</i>	1.19	(Spielman et al. 2007a)

Table 10-2 Comparison of energy analysis between biogas and other energy sources (* denotes a theoretical setup only)

10.5.1 Implications of biogas energy analysis findings

The analysis has demonstrated the energy inputs within a range of typical AD processes. This has enabled an understanding that biogas yield is affected by the feedstock type, operating temperature, retention time and the rate of feedstock input. Most of the energy input (up to 80%) of the AD process is concentrated within the plant itself (Berglund & Borjesson 2006). Within the AD plant, the majority of energy consumption is allocated to heating the digester, as the electrical demand for pumping and mixing is comparatively lower.

The average heat consumption determined for a number of plants was around 250 MJ/tonne whilst electricity consumption was recorded to be approximately 45 MJ/tonne. When considering the average operating temperatures of AD plants (commonly mesophilic at 30°C-40°C) it was apparent how critical the geographical location of an AD plant was. The electricity consumption meanwhile was found to correlate to the dry matter percentage (TS %) of the material. This was due to the dry matter requiring a greater amount of energy in order to displace and deform it.

The South West of England has on average an annual maximum temperature between 4°C and 5°C higher than the North of England and Scotland (Met Office 2007). Even within the South West there is a variation of temperatures across the region. The slightly elevated temperatures in this region could be favourable towards the efficiency improvements of biogas production.

The transportation of feedstocks was not found to be as energy intensive as expected, with other literature revealing that manure can be transported up to 125 miles before it becomes energy negative. Energy crops and other “exotic” feedstocks can be transported up to 430 miles, prior to becoming energy negative (Berglund & Borjesson 2006). The longitudinal distance of the region is around 200 miles on road, whilst latitudinal cover is only 90 miles by road. Therefore wastes can be transported across the region in order to maximise the digester size. Farms could therefore deliver to centralised AD units rather than having individual AD plants for each farm.

The energy analysis carried out on the three AD plant case studies highlighted clear correlations between the GER and the scale of the AD plant. Figure 7-8 showed that as the plant size increased the energy resource requirement decreased. This emphasized the potential benefits of large-scale AD over small-scale. Within the study it was also found that the use of high biogas yielding materials could be used to improve the ERE of smaller-scale AD plants (this could also be true for large-scale). Therefore it can be concluded that in order to maximise the energy output of biogas production, large-scale AD is favourable.

The use of high biogas-yielding food wastes as a main feedstock is not essential in achieving high-energy yields. This is clearly shown through the comparison between plant B and plant C. The feedstock for plant B is a mixture of food processing and farm waste, whilst plant C is predominantly farm manure waste. As the use of farm waste eliminates the requirement for additional (expensive) waste handling processes, it can be concluded that the benefits of using ‘exotic’ wastes are limited. However, by not using gate fees as a supplementary income, the implications on the revenue of the AD plant could mean that return on investment would be more limited. Relying on the revenues from landfill avoidance may not appear to be a sustainable (or a permanent) solution to the development of this technology.

The use of all-farm waste favours the South West of England due to its abundant source of animal manure. However, the performance of plant C was not due to the manure alone. An additional ‘booster’ feedstock or co-substrate is required if AD plants were to operate as successfully as the case study plant C. The co-substrate used there was maize silage, which is derived from crop processing wastes. In terms of volume or mass, the addition of this co-substrate is comparatively small against the manure feedstock quantity. However, the use of the feedstock adds to the energy requirement of the overall plant.

The exclusive use of animal manure within the AD process also eliminates the requirement for a pasteurization tank meaning the conversion process could require less energy. The digestate is considered and recognized as a natural form of fertiliser (DEFRA 2008d), whilst digestate from a mixture of wastes is not easily classified as a natural source of fertiliser.

When interpreting the results for the South West, it can be concluded that the optimal use of biogas from AD would either be for CHP or transport fuel. These uses for biogas showed the

highest net-energy yields. CHP could be installed within the region to either provide district heating for local villages or be used as a source of thermal energy for hot water and heating within the agricultural sector. An example of how this could be utilised is a typical small-scale dairy farm which can use up to 1000 litres of hot water (80°C) per day for washing and cleaning milking parlours.

The use of AD for the South West region could be favourable if a network of large-scale AD plants were strategically placed across the region around the locus of the farming population. The transport of animal manures to and from the farms would be outweighed by the energy output which large-scale biogas plants can produce; with the addition of a co-substrate. The preferred use for biogas within the region, based on energy analysis, would be either for combined heat and power (CHP) or use as a transport fuel. Further work could be carried out to analyse the exact location of the farms (along with their scale and waste output). Using this information and knowledge of main transportation routes within the region, the optimum location for centralised AD plants could be determined. One of the key considerations and possible limitations of CHP is the capital investment of district heating systems. A further analysis would provide a useful guide to the financial payback of this technique depending on the location of its installation.

10.6 Review of life cycle assessment results

The life cycle assessment (LCA) was carried out on one of the three case studies used for the energy analysis. Due to the complexity of LCA it was considered more accurate to undertake a detailed analysis for one AD plant. This is because LCA requires actual operating data to correctly simulate the environmental impacts of a process. The LCA was undertaken on the small-scale AD plant (plant A); as it was the only process to digest a single feedstock. This could then be used as a model for other AD plants within the region. Additionally, the plant also offered the largest operational and construction data resource.

The LCA study highlighted the potential contributions and detrimental effects that biogas production and use could have towards the environment. As expected, the use of biogas for displacing kerosene could offer benefits in terms of lowering CO₂ emissions and decreasing the consumption of fossil fuel resources. The use of biogas (as a replacement of kerosene for heating) was found to displace oil and/or gas-based fossil fuel resources.

Additionally, the output of the digestate was found to have positive benefits towards climate change and fossil fuel resource depletion by displacing energy-intensive inorganic fertilisers. Other environmental damages such as carcinogenic effects were found to be minimised if digestate were used as a displacement of inorganic fertilisers.

10.6.1 The potential of methane savings from biogas production

The benefits to climate change could have been greater if the displacement of naturally occurring methane from undigested slurry was also considered. The savings in methane due to the process of AD are very difficult to quantify and are often not credited within biogas-related studies (Ghafoori et al. 2006;Ghafoori et al. 2007). This is because 86% of the methane emitted is due to enteric digestion (i.e. emitted within the animal's digestive system), whilst only 14% of methane emissions are associated with the manure storage and handling (Mistry

& Misselbrook 2005). Methane emissions from storage are strongly linked to the surface area in contact with air. The greater the area, the lower the methane emissions produced (*ibid*). Therefore the uncertainty of how manure is stored can add greater errors when accounting for climate change benefits from methane savings.

The study did not take this into account as the methane yield from aerobically digested manure can vary significantly depending on its exposure to air. To reduce the inaccuracies within the study this additional benefit of biogas production was truncated outside of the system boundary. A list of rationale was created to justify this decision are as follows:

- Laboratory studies have shown that over a 30 day period, the gaseous emissions are predominantly carbon dioxide. Methane emissions contributed to around 2% (Dinuccio et al. 2008).
- Methane production from AD is significantly higher than aerobic methane generation, therefore exact manure storage techniques must be assessed for each individual case study of AD.
- Methane emissions from agriculture are predominantly associated with enteric digestion (86%) rather than waste storage and handling (Mistry & Misselbrook 2005).

10.6.2 Implications of biogas life cycle assessment findings

Although biogas production offered some environmental benefits, both outputs (biogas and fertiliser production) highlighted significant damages towards human health and the quality of ecosystems. These damages were found to impact respiratory inorganics and acidification/eutrophication. This was primarily due to the ammonia emissions during the production phase of biogas, the diesel and kerosene combustion and emissions from the biogas combustion (used for the production of further biogas).

Ammonia release was especially significant as it contributed towards both impact categories. These emissions could have been avoided if ammonia filters were put in place such as the ANAStrip process (Deublein & Steinhauser 2008). This could significantly reduce the impact of these environmental concerns, as it eliminates traces of ammonia within the process. Another technique would be to prolong the digestion period so that less ammonia is emitted during the digestate stage. A final recommendation would be to create a cover over the digestate tank in order to trap the post digestion emissions. This would not only reduce air emissions but also recover some of the remaining biogas.

Emissions such as sulphur dioxide and nitrogen oxide also contributed towards the environmental impact from acidification. These emissions were a result of the combustion of biogas and kerosene within the AD process. A recommendation could be to install a desulphurization procedure within the AD plant. This would eliminate the hydrogen sulphide within the biogas and subsequently eliminate the sulphur dioxide emissions from hydrogen sulphide combustion. These systems can range from very crude devices such as a container of iron filings acting as a filter for the biogas to pass through; to more expensive computer controlled gas cleaning processes (Ecofys 2005).

Another factor found to contribute towards these two environmental impacts was the low biogas productivity of the plant (i.e. a low capacity factor). The implication of having such a

low capacity factor meant that a larger amount of biogas was combusted per unit output of biogas produced. A recommendation for this AD plant would be to increase the feedstock availability and also increase the demand for biogas. These two measures would increase the capacity factor of the plant and therefore the impact of kerosene combustion (and excess biogas combustion) would be reduced. Currently the additional biogas could not be stored in the gas-storage tank as it was too small; therefore excess biogas was used to overheat the digester. To improve this inefficiency, a larger biogas storage tank could be installed.

Installing these emission controlling techniques may require additional energy consumption and expenses; however the overall environmental benefits would clearly be significant. The use-phase of the AD plant was found to contribute most towards the environmental impact categories over the whole life of the plant. These emission measures would therefore have an impact over the most critical part of the life cycle for biogas production.

Environmental concerns such as fossil fuel resource depletion were also found to be caused by the inefficiencies within this specific AD plant. In particular these were the high start-up kerosene use, the excess biogas burnt within the digester due to lack of demand from the farm-house and the diesel consumption within the farm for collecting and handling the waste. The impact of the latter did have an element of uncertainty and was shown that it could be reduced within the sensitivity analysis. The implications of these findings are that the environmental impact of fossil fuel resource depletion should not be representative for all AD processes. This is because these inefficiencies are site specific and could easily be reduced through improved process engineering design.

The findings from the whole life cycle assessment of the AD plant showed that the plant could have a positive impact on climate change (Figure 8-11). This was primarily affected by the avoidance of kerosene combustion but also the biogenic use of carbon dioxide during the AD process. Therefore the findings advocate the carbon dioxide emissions savings through the use of biogas from AD. As the LCA study considered the use of animal manure as a free resource, the impact of using biogenic CO₂ as a resource should be considered carefully. In this study this has been addressed in section 8.7.1.2.

10.6.3 Recommendations for the South West of England

Implementing the use of AD for biogas within the South West of England could offer environmental benefits in terms of lowering GHG emissions and the consumption of fossil fuels resources. However adopting a similar setup to the AD plant analysed for the LCA would offer questionable benefits towards the environment. The design of the AD process should incorporate air emission reduction measures such as desulphurization, ammonia reduction and process efficiencies. The impacts of not using these measures were made clear through the LCA. If these measures were not put in place on large-scale AD plants then the effect of these impacts could be even greater.

It is also recommended that stringent legislation should be put in place for the use of food wastes within the AD process, as is the case in case study plant B. The use of undigested food wastes also emits higher emissions in terms of ammonia, hydrogen sulphide (Deublein & Steinhauser 2008). As a result adopting these feedstocks could amplify the problem further making it essential to ensure that air emission reduction measures are implemented on all AD

processes. The design of the AD process must also consider the feedstock production/collection process. The results in Figure 8-11 showed that the balance of climate change impact between production and use of biogas was very similar. This plant did not have additional energy expenditures in terms of feedstock production or collection. If these were present, the balance may not have been as neutral.

In conclusion, if a scenario were adopted similar to those described in 7.4.5, biogas production could contribute significantly towards the region's energy supply and lower its impact on climate change (shown in Figure 8-11). Additionally, the natural fertiliser (digestate) could displace inorganic fertiliser use in a region which is heavily dependent on farming (over 80% of the regional land is dedicated to farming). Therefore the potential for using AD should not be overlooked.

Regulatory measures must be taken however, if this technology were to be implemented to a large scale within the region. The LCA highlighted the potential damage which the AD process contributes towards human health and ecosystem quality. It is recommended that biogas production facilities are installed with the correct and adequate emission control systems as previously mentioned. Filtration and cleaning techniques in AD plants are vital as without these measures the emissions have a significant impact on human health and damages to ecosystems which could overshadow the displaced fossil fuel and climate change reduction benefits.

The LCA has provided a scientific means of relating the AD plant design process and the capability to minimise the environmental damage of biogas production. Despite the uncertainties within the LCIA methodology adopted, the tool has nonetheless provided a valid assessment of the areas in which AD design must be improved.

10.7 Review of financial investment appraisal results

A financial investment appraisal for biogas production and use has shown that under certain conditions, AD can be financially profitable. This is affected by the export value and costs of biogas production. Investment costs for AD plants were found to be approximately £20,000-50,000/tonne of feedstock input per day. Other sources related the investment cost to the digester size. Adopting this approach showed that AD setup costs are in the region of £220-650 per m³ of digester. However, the results in Chapter 6 showed that the daily input rate and the digester size were linearly proportional. As a result, it can be assumed that both capital cost relationships are valid.

However, reviewing Figure 9-1 shows that the relationship is not completely linear and that capital costs/AD size could decrease as the plant size increases into large setups. Additionally, the fluctuation of results from the mean was also noticeable. This implies that using average figures to calculate the capital cost of AD plant setups does not give a representative result and without knowing the auxiliary equipment within the plant (such as CHP, biogas cleaning etc) these averages can be misleading.

The primary cause of this uncertainty is that AD setups vary greatly in terms of auxiliary equipment installations such as desulphurization units, varying sizes of biogas storage which

are dependent on demand and different end-use conversion technologies for the biogas itself. Additionally the tank construction can vary from concrete, steel and even polymer. These too could have an influence on the capital cost of an AD plant. As a result, the averages found for capital costs could provide a broad capital cost indication, whilst detailed site assessment should be carried for individual plants.

The capital cost for a large scale AD plant (using the same digester size) was found to vary between £400,000 to just under £1 million. A large scale plant such as this is capable of producing around 1,500 cubic metres of methane per day (53.7 GJ per day). Converting this biogas to electricity would provide 5,000 kWh per day. Assuming a 20-year lifespan and a capacity factor of 80%, this equates to around 1.4p/kWh up to 3.4p/kWh of total lifetime electricity production. If AD installations were to be implemented for electricity production, the investment costs of the plant would have considerable impact on the unit cost of electricity production. The cost of electricity production could vary by over 100% depending on the initial capital cost of AD. In addition to this, the operation and maintenance costs would also increase the production costs of electricity.

By re-examining the financial support mechanisms supplied by the UK Government it is clear that one-off grant schemes such as the capital grant scheme are insufficient as the annual operating costs can nearly match the total capital costs. As a result, support mechanisms should be a continuous funding stream, in addition to the ROC and FIT schemes which only reward the performance of a bioenergy project. However, funding is limited during the initial stages of a bioenergy project where there is a greater risk of downtime or technical issues. A solution to this would be to have gradually decreasing financial support mechanisms. This would offer higher rewards during the initial phases of the project, which would then gradually reduce over time. This could help during the initial phases of the project up to when the bioenergy plant can operate successfully with minimum downtime.

Given the recent doubts cast over the application of bioenergy as a transport fuel, the drive for crop fuels such as bioethanol and biodiesel remains uncertain (The Royal Society 2008). The use of biogas as a transport fuel is technically less challenging as cleaned biogas is a direct replacement of liquefied petroleum gas (LPG). Additionally this technique is a method of utilising waste and converting it to an energy source for transport. A recommendation would therefore be to implement greater incentives for the use of biogas as a transport fuel as this energy source has unique potential within this sector. The use of biogas as a competing energy source against other uses such as electricity and heat production may not be maximising the potential of this energy source.

Although the use of biogas as a transport fuel appeared to be financially plausible, the uncertainties within the calculated results were clearly highlighted in Table 9-5. The analysis showed that both (electricity production and transport fuel production) options could be financially feasible depending on the assumptions made. As a result the sensitivity analysis highlighted how these assumptions can impact the outcome of the financial investment appraisal. The study highlighted that theoretical economic modelling cannot be used to accurately assess the financial feasibility of an AD plant setup. Having used a number of the available economic models, it is apparent that there are significant limitations with each of these models, which have been detailed in section 9.3.

The financial feasibility of adopting biogas production for the South West was modelled using the AD case-studies for plant A and plant C, the latter showing the best performance in the energy analysis study. These two case studies were used to address two areas of interest: firstly to allow a comparison between the financial appraisal of a large and small scale AD setup, secondly to assess the financial viability of an AD plant which could use feedstocks indigenous to the South West of England.

Plant C performed well in terms of net-energy output but was also well-suited to the resources available within the region. If plants of this scale were adopted for the South West of England a significant contribution of animal manure could be used as a feedstock. The total dairy cattle population in the region is around 650,000 which would in theory equate to the construction of around 260 AD plants of this scale. This would obviously vary depending on the size of the plants constructed.

In order for these plants to operate in accordance to the case study example, 220 ha of maize silage per plant would be required per year. For the total region, this corresponds to around 57,000 ha of maize plantations. In 2007 the region produced 58,000 ha of maize, all of which were converted to maize silage for animal feed. An AD operation of this scale would require nearly all the maize production allocated to the South West. Using this crop extensively as described could have serious implications on the animal feed market, ultimately leading to a potential price hike for this feedstock.

A scheme of such scale (260 large scale AD plants for the SW of England) could produce an annual regional revenue of between £78million to £225million depending on the biogas end-use and the associated retail value of different AD outputs. However the extensive use of maize silage could ultimately lead to more expensive animal products such as meat and dairy. These external costs were not taken into account within the study as it is not usual practice to do so in a financial investment appraisal.

It is clear that careful attention should be made to the displacement of arable land for the production of biogas; or for any other bioenergy resource. Although the production of biogas through this scenario requires comparatively little arable land for operation, the impacts are still notable. If the use of energy crops for AD were increased or adopted for another bioenergy conversion technology such as fermentation or transesterification, then considerably more arable land-use would be required. This could have a negative environmental impact as increased artificial fertilisation and transport may be required.

The need to examine the external costs associated with biogas production is therefore a recommended future investigation, to enable an understanding of the true economic costs and benefits of this bioenergy pathway. External costs such as animal feed displacement and increased detrimental effects towards the environment should be assessed as this would be representative of the issues for the South West region.

In conclusion, biogas could be financially viable and potentially suitable for the South West of England due to the abundant animal manure and land availability for agricultural crops. Although biogas production for transport fuel performed financially better, in reality the probability of using the gas in this way would be limited. This could be predominantly due to

the limited use of LPG vehicles (suitable for adapting to biogas). However, as highlighted previously, the Government financial rewards of using biogas as a transport fuel are not as clear and direct as support for electricity and heat production. These issues could influence the end use of biogas, by generating a greater use of the fuel for electricity and heat production than for transport fuel.

10.8 Summary and outlook on bioenergy for the South West

The wealth of bioenergy resources in the South West of England offer a potential to pursue the targets set in the UK's Biomass Strategy (BERR 2007c). There is a clear supply of substantial biomass resources in the region; resulting in the potential for the South West to play a major/leading role in bioenergy for the UK. The study has shown that biomass resources are not fully maximised within the region. This appears to be primarily due to economic and technical constraints raising the cost of bioenergy deployment. Public perception of bioenergy plants can be linked to the uncertainty of technologies and can create obstacles for planners and developers. Examples of this include the failed 21.5 MW biomass gasification site in Winkleigh, Devon (Upham & Shackley 2007; Upham & Shackley 2006) and the failed North Wiltshire 5 MW wood gasification plant (Upreti 2004; Upreti & van der Horst 2004).

At present, conventional energy-production techniques are less expensive, more abundant and readily available. As a result the need for biomass as an energy source is limited. Additionally, the financial reward incentives for consumers to opt for 'greener' technologies could still be a suitable driving force across the whole bioenergy spectrum.

As there are established incentives for renewable electricity (Thornley 2006), this could mean that at present the favourable use for bioenergy is electricity generation. This is further subsidised by the newly implemented Feed-in-Tariff (FIT), thus increasing the drive for electricity production from bioenergy. These established financial reward mechanisms may drive the use of biomass away from the potential of heat generation or conversion into transport fuel.

Biomass has a significant potential for renewable heat generation (Slessor & Lewis 1979). If bioenergy for heat energy were to be subsidised in a similar way to electricity generation, there could potentially be an increase in uptake of biomass for heat. This scheme is envisaged to be implemented in the near future through the renewable heat incentive (DECC 2010b). Additionally, bioenergy feedstocks are generally available in rural areas, thus making them attractive for heat generation in the South West of England. Nonetheless, the expensive transport costs due to biomass' low energy density make it unfavourable in urban areas. This could be overcome by transporting the biomass in other forms such as wood pellets, pressurized biogas or bioliquids (bio-oils, biodiesel and bio-ethanol); therefore these routes should be investigated further.

It is difficult to estimate the plausibility of exploiting bioenergy as a transport fuel. The biogas studies within the thesis have shown that on energy and financial levels this bioenergy pathway could be favourable. It would be difficult to quantify the contribution which bioenergy could have on reducing carbon emissions and fossil fuel reduction targets, as transport energy use is not contained solely within the region. Additionally, the lack of clear

financial incentives for renewable sources to enter the transport sector will also deter the use of bioenergy to be confirmed for this use.

10.8.1 Limitations of the resource assessment and examination of barriers & drivers

The resource assessment carried out was an extensive and detailed representation for the South West of England. Due to the scope of the research it did not show how the region compared to other regions and therefore could not address whether bioenergy should be solely focused on development in the South West or in the UK as a whole. The level of detail at which the resource assessment was undertaken would require a period longer than the allocated time for this research (based on the time consumption for the SW resource assessment). Additionally, the resource assessment is a tool for understanding how and which resources should be used, thus it is not a comparative tool to assess different regions.

A number of limitations were observed after examining the barriers and drivers for bioenergy. The number of stakeholders which contributed to the survey could have limited the study undertaken, as documented in Chapter 4. Due to the relatively low number of stakeholders available and willing to participate, the assessment had to consider bioenergy as a whole. This was not preferable as it was acknowledged that there would be different barriers and drivers for each bioenergy pathway. However, due to stakeholder limitations bioenergy was considered as a whole and interpreted accordingly. Nevertheless, the results have been invaluable and were well received by peers (Adams et al. 2008).

10.8.2 Limitations and recommendations of the analysis in this thesis

The initial objectives set out for the research assignment were to assess the potential of bioenergy for the South West of England, covering all bioenergy feedstocks and pathways. The thesis has shown that a valid and representative assessment of bioenergy should assess bioenergy pathways individually. Although the study undertook an extensive multi appraisal technique there were still key areas of research which were identified for possible future analysis for the pathway of biogas production.

Further analyses could include examining the environmental impacts for a range of biogas production plants, covering a variety of feedstocks and biogas end-uses. This would highlight the potential environmental impacts of each bioenergy pathway on a broader scale. Similarly the costs of the environmental impacts should also be calculated and linked to the external costs and benefits of using biogas within the region. The current financial investment appraisal highlighted the issues concerning the large-scale adoption of maize silage as a feedstock for biogas production. However, due to the nature of a financial investment appraisal these externalities were not considered.

The assessment of bioenergy pathways in this method can be time consuming and may only represent one particular set-up within the pathway. However a study such as this clearly highlights the overall sustainability of a bioenergy pathway in terms of energy, environment and economic implications. An overall recommendation would be to carry out a similar assessment for all suitable bioenergy pathways within the region. Once carried out, a matrix of outcomes could be used to determine the most suitable bioenergy pathway based on energy, environment and economic aspects.

11 CONCLUDING REMARKS AND RECOMMENDATIONS

11.1 *Introduction*

To determine the potential of bioenergy, an array of scientific and engineering based research techniques were required. These techniques were crucial in developing an understanding of the true potential of the energy source, in terms of resource estimation, energetic output and feasibility of implementation, financial consideration and assessment of the environmental impacts.

This chapter aims to draw conclusions and make recommendations based on the original research objectives. The significance and impact of the results obtained from the various studies are also discussed. The closing views and considerations of the biogas potential for the region are addressed, focusing on the results and trade-offs obtained between some of the analysis techniques.

11.2 *Initial research objectives*

The initial research objectives were as follows:

- Examine the bioenergy resource potential for the South West region. This should be done in terms of actual and theoretically obtainable potential.
- Examine the drivers and barriers to bioenergy development and use for the region.
- Considering one bioenergy pathway (biogas); assess the potential of biogas use within the region based on the following criteria:
 - Energy analysis of biogas production systems.
 - Environmental appraisal of biogas production and its impacts.
 - Financial investment appraisal of biogas for the SW of England.

11.2.1 **Examine the bioenergy resource potential for the South West of England**

The resource assessment was conducted in accordance with established and published resource assessment methodologies. The assessment highlighted that the current highest contributor to bioenergy in the South West was energy recovery from waste. This provided the majority of the (rather small) energy contribution to bioenergy for the region. However, there appeared to be signs that other biomass sources were being adopted for bioenergy purposes.

The resource assessment highlighted the large contribution which farming made towards the overall land use (over 80% land use). Subsequently, this emphasized the potential of farm waste as a source of bioenergy. Due to the extensive land availability for crop farming, it was concluded that the region could offer an excellent contribution to bioenergy by harvesting annual and perennial crops, such as oilseed rape, wheat, miscanthus and short rotation coppice. However, with the abolishment of set-aside land in 2007, the production of bioenergy crops has competed directly with food crop production. This factor, along with additional uncertainties regarding first generation biofuels, means that energy from waste could offer a substantial contribution without affecting the region's established farming sector.

11.2.2 Examine the drivers and barriers to bioenergy production and use in the region; also examine the social impacts of bioenergy

The study focused on understanding why a significant number of prosperous bioenergy projects launched in early 2000 had not materialised by the end of the decade. The analysis called for an understanding of the key barriers and drivers for bioenergy production across the whole supply chain: farmers and suppliers of feedstock, bioenergy conversion owners/developers, bioenergy primary end-users and finally, Government related bioenergy stakeholders.

A stakeholder survey was undertaken to establish the most important barriers and drivers to the development of bioenergy. The study highlighted a strong link between the whole supply chain for bioenergy development and the importance of Governmental assistance at each stage of the bioenergy development chain. The main focus lay within economic aspects of bioenergy projects. This was clear from both a drivers and barriers perspective. It was determined that the primary consideration for bioenergy schemes must be that they are economically attractive, which then dictates the success of a project.

However, the importance of bioenergy in its ability to reduce carbon emissions and fossil fuel dependency was also seen as relatively significant. It highlighted the need to demonstrate the net-energy and carbon benefits of a bioenergy scheme. Supply of resources was highlighted as a critical issue, confirming that bioenergy can often compete for land-use against other crops.

Across the whole study, the social impacts of bioenergy development were appreciated. In this particular study the stakeholders were asked whether public perception was seen as a key barrier to bioenergy development. The results showed that this barrier was not amongst the most significant. However, studies referenced extensively throughout this thesis suggested that one of the most common causes for failed bioenergy developments was strong public opposition to planned projects.

11.2.3 Assess the net-energy of biogas production and how this affects the region

The use of biogas was considered as a suitable option for bioenergy production within the South West. The net-energy benefits (or drawbacks) of biogas production were analysed. The analysis followed standard, established conventions for assessing the net-energy of a process. The results highlighted that small-scale biogas plants appeared to produce less energy than the energy invested over their lifetime, therefore being an energy sink. However, this was highly dependant on the feedstock input, the operating capacity and the energy quantity having to be invested in the plant.

Large-scale AD plants proved to be much better in terms of net-energy output, compared to small-scale AD plants. However, the analysis also highlighted that farm-derived wastes could be just as, if not more effective than using industry or food processing wastes. This was due to the increased energy requirement to pasteurize and process materials that pose a hygiene risk. The theory of energy analysis also highlighted the variation of results depending on where the study system boundaries were placed. If the energy benefits of natural fertiliser production were accounted for then the AD plants produced an improved net-energy output.

Based on the most energy efficient plant analysed within the energy analysis, it was estimated that around 260 AD plants of this scale could be installed in the region; based on the feedstock availability.

11.2.4 Assess the environmental impacts associated with the deployment of biogas production in the region

Life cycle assessment (LCA) was used to determine the potential environmental impacts of AD. An LCA was carried out on a single AD plant (denoted as plant A in the case studies). The LCA showed results that met preconceived expectations in terms of the potential for the reduction in fossil fuel resource depletion, along with a potential reduction in climate change impacts during the entire lifecycle of biogas production. These were mainly achieved by the displacement of kerosene and inorganic fertiliser production. However, these benefits were at a cost of increased damage towards human health and ecosystem quality. This was due to emissions from the process which contributed towards respiratory inorganics and acidification/eutrophication. These were found to be a result of ammonia emissions during the digestate storage, followed by diesel and kerosene combustion during the production phase of biogas.

It was found that these damages could be significantly reduced if appropriate emission control measures were undertaken. This included: covering the digestate storage so that less emissions were able to escape during the post-digestion process; introduction of an ammonia removal process, currently commercially available; inclusion of a desulphurisation unit to reduce sulphur dioxide in the combustion process and finally installation of catalytic converter units on biogas combustion processes to reduce further nitrogen oxide emissions.

The analysis concluded that if biogas were to be installed in the region, careful measures should be undertaken in order to minimise the impacts towards respiratory inorganics and acidification/eutrophication. The benefits obtained from biogas production would be outweighed by the increased damage to human health and ecosystem quality. The emission reduction procedures should be made obligatory if biogas production were implemented in the region.

11.2.5 Assess the use of biogas based on a financial investment appraisal

The study examined the production and use of biogas based on a financial investment appraisal. The assessment examined the variation in plant scale, along with the variation in biogas feedstock and end-use. The investment appraisal highlighted the possible financial benefits of adopting large scale AD in the region, due to the region's abundant resource supply. The study concluded however, that co-substrate addition for a large AD development in the region would require a significant amount of cropland (even if the co-substrate addition per plant were very small, i.e. less than 10% per AD plant).

The study highlighted that the unit selling price of electricity and biogas transport fuel was similar in some circumstances. Due to the low conversion efficiency of electricity production a lower amount of marketable energy would be obtained from this process. As a result, biogas for transport fuel production was found to be more profitable. However, as profitability is linked to demand, it is envisaged that the demand for biogas for transport will be much lower

than electricity production. The study concluded that biogas production could contribute towards £78-225 million annually for the region, depending on the end-use of biogas and the investment costs. However, careful consideration would have to be made to check other markets (such as the maize production market in the SW) would not be impacted by biogas production.

11.3 Issues found from attempting research

The initial research objectives were created with a holistic view of bioenergy. The research was intended to focus on a broad range of bioenergy types, focusing on a particular geographical region. This was achieved in part by conducting a resource assessment for bioenergy, as all biomass types could be examined. However, subsequent research objectives, such as energy analysis, environmental assessment and financial assessment posed a greater challenge in creating detailed research for such as broad range of bioenergy pathways.

Appreciating all bioenergy feedstocks, conversion processes and end-uses highlighted the extent of the bioenergy pathways. It was concluded that in order to achieve the level of qualitative research required, a single bioenergy pathway would have to be analysed.

As a result, the pathway was selected based on the results from the resource assessment, where organic waste was highlighted as one of the most abundant and least impacting resources on current markets. The issue with this approach was that many other bioenergy pathways which could have been beneficial for the region were excluded. However, to carry out an interdisciplinary integrated appraisal methodology for just one bioenergy pathway proved extremely time and resource intensive. The issue therefore, may have been with the initial research objectives either being too ambitious or not fully understanding the time resource requirements for undertaking energy analyses, environmental impact assessment and financial appraisal techniques.

Having limited the scope of the research to just one bioenergy pathway enabled a true understanding of the potential for this pathway within the region. Additionally, the outcome of the research could provide a blueprint procedure for assessing the suitability of other bioenergy pathways for particular geographical regions.

11.4 Overall contributions from research findings

The thesis represented an extensive and detailed study of bioenergy for the South West of England. The resource assessment methodology detailed in Chapter 3 identified that the use of bioenergy in the South West of England was considered to have a strong potential. Furthermore, few detailed studies had been previously undertaken to determine what sort of biomass was available and how the biomass could be used to optimise the production of bioenergy. Therefore this resource assessment makes a valid contribution towards the region's appraisal of bioenergy. The study also enabled an understanding of the motives for the region's (and UK in general) lacklustre deployment of bioenergy. The links between the drivers and barriers of bioenergy enabled an understanding of the motives for slow bioenergy development. This is an important factor when addressing future bioenergy developments for the UK; to gain a clear understanding of why previous bioenergy project attempts have failed.

The outcome of the resource assessment highlighted that one of the most feasible uses of biomass for bioenergy was the exploitation of organic matter for biogas production. In a region such as the South West where farming has an important role, the use of land is critical in maintaining the economic and ecological structure of farming within the region. Therefore reducing the land requirement for biomass in the region could be beneficial. Introducing the use of bioenergy (on a scale large enough to make a significant contribution) could have serious implications of the delicate and established farming life within the region. For this reason, the use of biogas for bioenergy could be a plausible solution for the region. However the scale and overall size of implementation should be examined in greater detail. In this thesis, the author was hesitant to elaborate on the proposed scenario of 260 AD plants, as this was used solely as a representation of the theoretical potential, but was not considered realistically feasible for the region due to uncertain environmental and economic outcomes.

The research concluded that large scale biogas production was favourable compared to small-scale applications. This was highlighted through the energy analysis but also through the LCA analysis where the inefficiencies of small-scale AD were clearly emphasized. Within the energy analysis, it was also concluded that biogas for transport would result in the highest energy gain. However, the use of biogas could only be used as a replacement fuel within liquefied petroleum gas (LPG) fuelled vehicles. Currently in the UK, the number of LPG fuelled vehicles is significantly fewer than petrol or diesel vehicles. Therefore, the limited supply of biogas for this energy-use would significantly reduce the beneficial impacts of the fuel. A more suitable use for biogas appears to be the combination of electrical power and heat production (CHP). The electricity could be used to feed the national electric grid whilst thermal energy could have more localised uses such as industry and agricultural implementations through district heating systems.

11.5 Further work

The research on the feasibility of biogas production and use enabled an understanding of the impacts of energy resource requirements for biogas as fuel. One of the energy requirements was found to be the transportation of feedstock to and from the AD plant. It was understood that there would be a trade-off between transport distances for feedstock collection and the amount of net-energy which would then be obtained from the biogas production. As a result, an extensive attempt was made to obtain exact locations of the farms in the region, along with feedstock types and quantities. However, the author was informed that due to privacy laws, it was forbidden to share such information. This information could have been used to determine the optimum location and size of biogas plants across the region, in order to maximise the net-energy benefits of the plant.

This is a potential area for future work, in order to complete an extensive analysis of bioenergy potential for the region. A list of other possible future work for the region has been shown below:

- Finalise the suitability-assessment of biogas by:
 - Analysing the farm location (and feedstock availability) to determine the optimum transport distances and AD plant size for the region;
 - Carry out an LCA assessment for a large scale single source AD plant and an LCA for a large scale mixed source AD plant. Use these findings to compare the results. These LCAs would have to be done with the same system boundaries and process assumptions as the LCA in Chapter 8;
 - Examine the indirect costs of this technology by assessing the external costs and benefits. This would require the use of Cost-Benefit Analysis techniques;
- Carry out a similar study as shown in Chapter 4 (assessing bioenergy drivers and barriers) for specific bioenergy pathways including biogas production; biofuels production and use; energy crops for electricity and heat etc.
- Carry out the multi appraisal technique (energy analysis, environmental assessment and financial feasibility) for other bioenergy pathways, which could be used within the region. Use these results to create a comparison of different bioenergy pathways for the South West.

11.6 Overall concluding remarks

The thesis has assessed the bioenergy potential within the South West of England with a particular focus on one bioenergy pathway. The thesis has used a range of techniques to determine the resource, production and use of biogas energy. The range of techniques has created a basis on which future appraisal methods could be carried out when assessing the suitability of bioenergy projects within a region. The multi appraisal technique has formed a possible blueprint methodology for decision makers and investors wishing to deploy the use of bioenergy.

The appraisal technique appeared to have a number of small flaws and these limitations have been addressed, followed by recommendations. The main uncertainty arose when addressing the outcomes of the environmental impact life cycle assessment (LCA). The use of LCA produces clear and powerful results; however, the risks of errors in achieving these results are currently very high. This is due to the volume of data required and number of assumptions which have to be made during an LCA. Although this technique is an established tool, there is still a lack of uniformity amongst LCA practitioner's approach when undertaking the assessments. These affect the outcome of an LCA and therefore reduce the evaluation capability of it. The study clearly showed the need to carry out a range of appraisal techniques to highlight the true potential of bioenergy. A single technique, such as LCA alone would not create a comprehensive and representative view of a bioenergy pathway's potential.

Overall, the research concluded that there is a strong potential for bioenergy within the region. The use of sustainable bioenergy, regardless of the feedstock, is closely linked to land-use and ultimately the farming capacity of a region. Notwithstanding the greatest efforts to minimise

the influence on existing economic and ecological farming characteristics within the region, ultimately the use of bioenergy will affect this sector.

The research has clearly highlighted the further analysis that ought to be undertaken to finalise the ultimate suitability of biogas production within the region. Additionally, the multi appraisal technique should also be used for other bioenergy pathways which could be favourable towards the region's energy supply. This would give a clearer representation of the true bioenergy potential, not just a single pathway. The research outlines this technique as a possible standardised method of assessment for future bioenergy projects for the UK as a whole.

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APPENDIX A

HEAT AND ELECTRICAL ENERGY DEMAND COMPUTATIONS FOR ANAEROBIC DIGESTION (AD)

Heat Energy Use for AD

Due to data availability the two primary factors; digester volume (related to input quantity) and the difference between digester temperature and ambient temperature were assessed. The power-law correlation shows the relationship between size and rank in a sample, represented by an equation in which the independent variables are raised to powers. By using the 'power-law' correlating equation, the heat energy requirement (Q) can be expressed as a function of these parameters as shown below.

$$Q = f(V, \Delta T)$$

This can be re-written using the power-law technique by:

$$Q = k[(V^a)(\Delta T^b)]$$

Where k is a constant and the constant a and b denote the dependants of the variable towards the outcome of the equation (the heat requirement). The two dependencies were plotted against the heat energy requirement and have been shown below (Figure A1, Figure A2 and Figure A3).

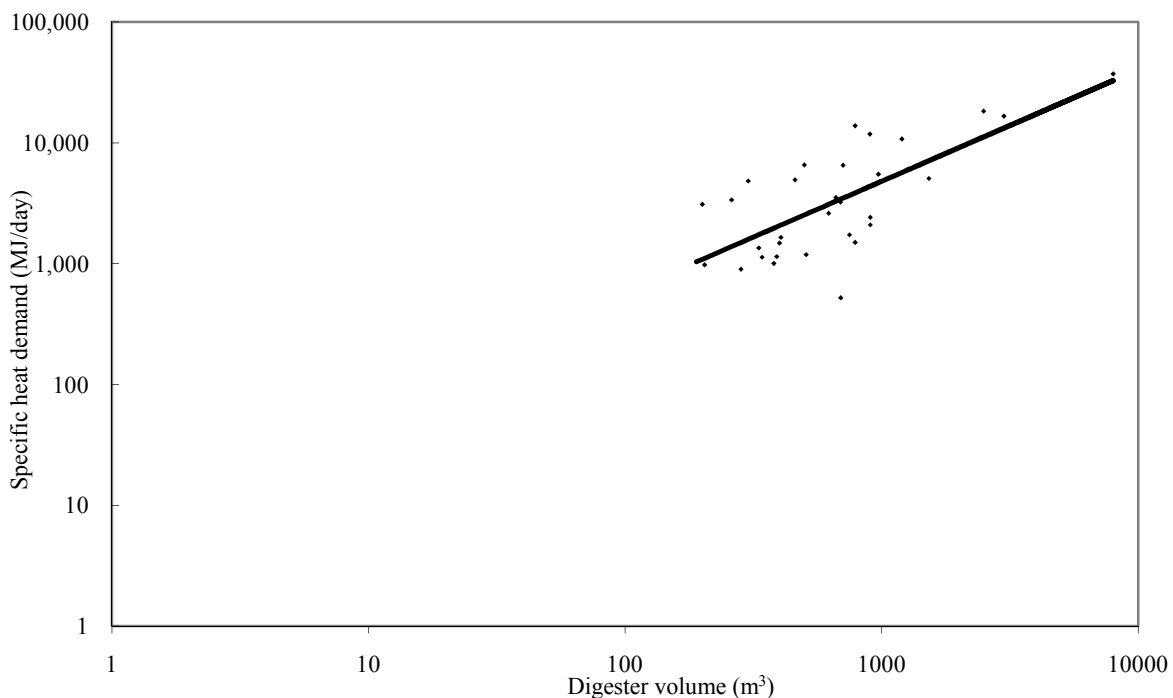


Figure A1 -Heat energy demand of anaerobic digestion vs. digester size

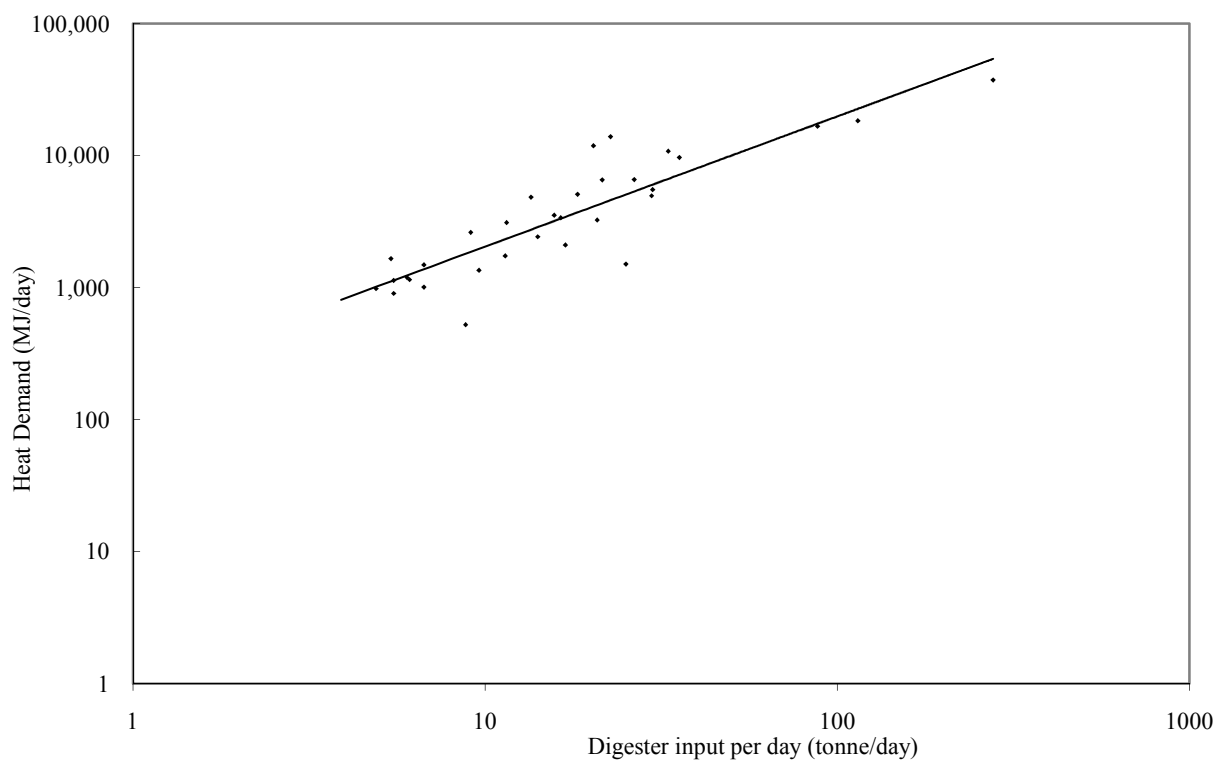


Figure A2 - Heat energy demand of AD vs, feedstock input per day

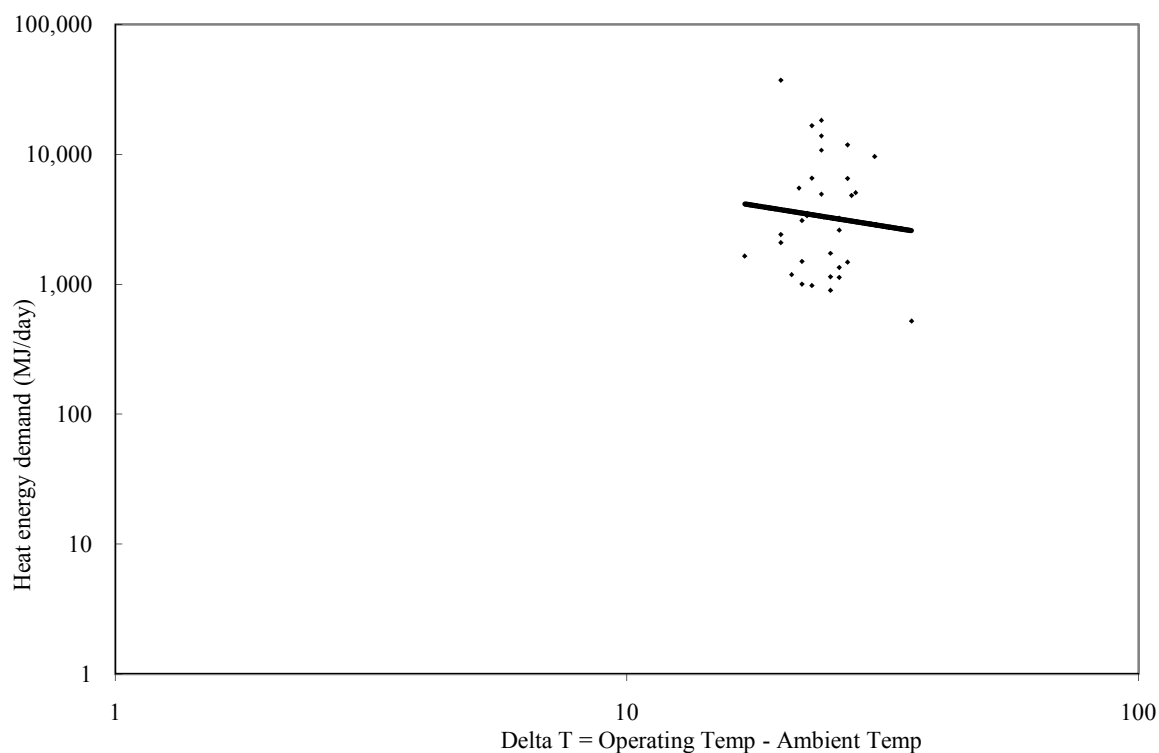


Figure A3 - Heat energy demand for AD vs. delta temperature

The results from the graphs in Figure A1, A2 and A3 highlight the level of dependency between the parameters. It can be seen that the digester volume, which is also linearly correlated with the daily feedstock input quantity, is heavily dependant on the heat energy consumption (over nine

tenths 9/10), whilst the operating temperature is significantly lower at around (with a dependency of two thirds 2/3).

However the scatter of the temperature results also represents a large potential error in the correlation. The large scatter could be contributed to by the difference in insulation materials chosen for the AD plants analysed. In addition to this, a base ambient temperature of 15°C was also assumed. In reality the ambient temperatures would differ between the plants and hence would ultimately lead to different results.

Electrical energy consumption for AD

The use of electricity in the plant is dependant on: the size of the digester (V), the daily input of feedstock, the flow characteristics of the feedstock ($TS\%$) and the time which the digester is operating for (retention time, RT). However electricity consumption per day is not dependant on the RT . This can be represented by:

$$W = k[(TS\%)^a](V^b)$$

Where k is a constant and the constants a and b represent the value of dependency of these parameters against the electricity consumption (W). The first correlation, shown in Figure A4, highlights the dependency of the daily input feedstock (m^3/day) on the plant electricity consumption. As can be seen the dependency is relatively low at around 0.37 (approximately 2/5).

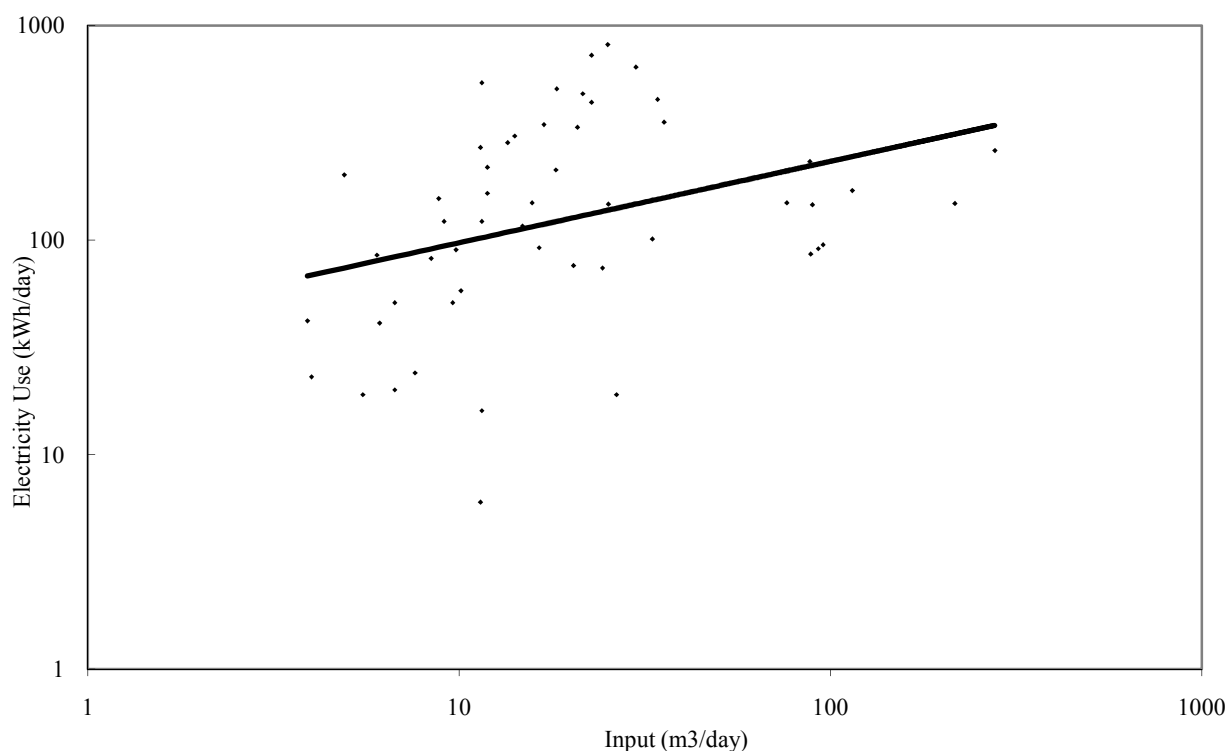


Figure A4 - Electricity generation vs. feedstock input of digester for AD plants

Analysing the correlation further also showed that the results highlight a significant amount of data scatter (Figure A4). This is due to the analysis taking into account a number of single and multiple stage digesters which are independent of the daily feedstock intake. Therefore this will have a significant impact on the ultimate electricity consumption.

When analysing the likelihood of the material's resistance to deformation (linked to the TS% of the material), the results show a much higher dependence between the TS% and the plant electricity consumption. This has been shown in the Figure A5.

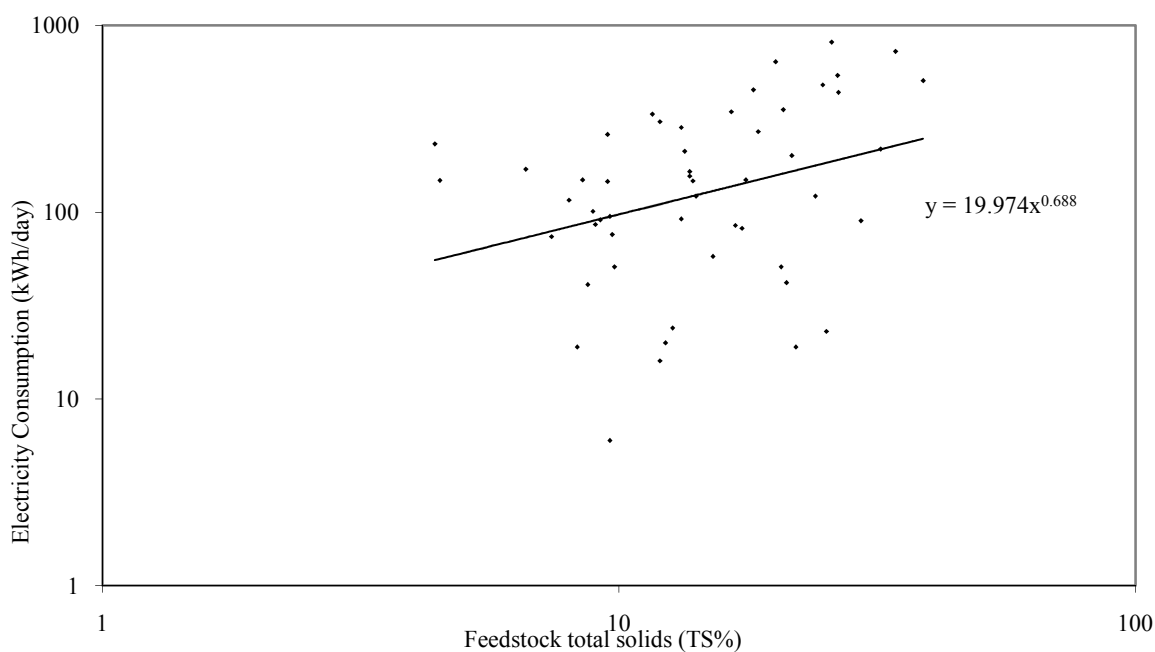


Figure A5 - AD electrical consumption vs. feedstock total solids (TS%)

The results highlight that there is a greater dependency on the material composition than the amount of feedstock entering the AD process. This shows the difference between electricity consumption dependency and heat consumption dependency.

APPENDIX B

BACKGROUND AND CALCULATIONS FOR LIFE CYCLE ASSESSMENT (LCA)

Alternatives to LCA

There are a number of other methodologies capable of assessing the environmental impacts of a process or product. These techniques are applicable to different circumstances, stages-of development and end-user requirements. Environmental Impact Assessment (EIA) for example is a technique of predicting the environmental impacts of a process prior to construction, through the compilation of an Environmental Statement (ES). The EIA is prepared based on a specific plant or site and therefore is site specific. However, this type of assessment can be generic as plant or process details are not considered. Risk Analysis is a technique of assessing the environmental, health and safety risks associated with a plant or site. This can be done pre or during the plant operation and is often continuous. Risks are site dependant and therefore are localised. Finally, design-for-x methodologies can also help designers in the initial and detailed design stages, to simulate the potential environmental impacts of a product or process.

These environmental tools can be placed on two axes depending on whether they are time or location dependant. A useful comparison of these tools has been created by Hofstetter (1998) and has been re-created in part in Figure B1.

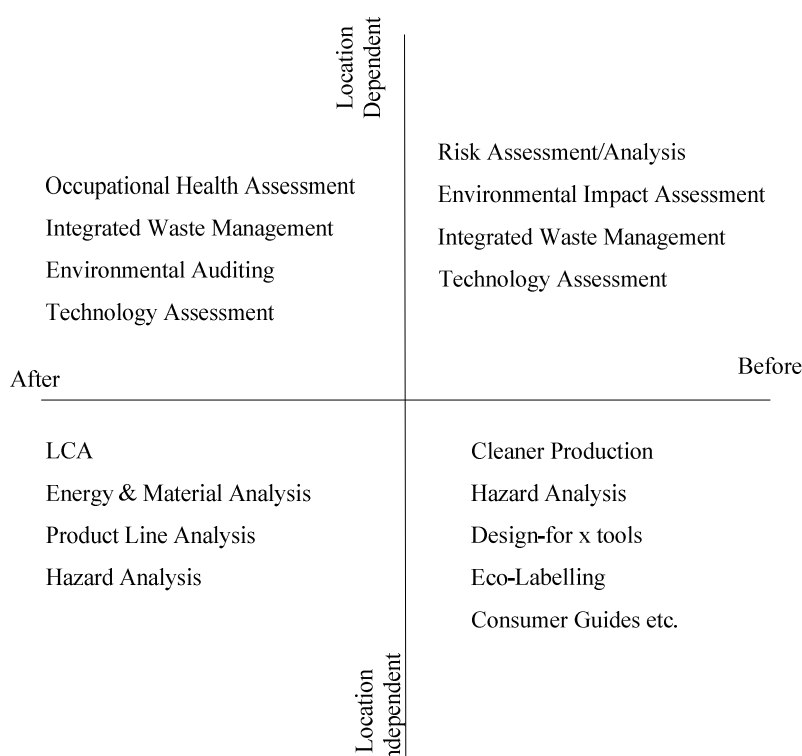


Figure B1 – Assessment of environmental tools relative to location and time. Adapted from Hofstetter (1998)

Calculation of the breakdowns for LCA

Life cycle inventory data - Manufacturing of anaerobic digester (Table B1)

This section highlights all the construction materials used for manufacturing the AD plant. The list also highlights the appropriate references from which the data was obtained.

- (a) – Data based from dimensions obtained from the plant, a reconstruction of the plant layout using solid edge 3D CAD package and understanding the techniques from the Permastore (2009).
- (b) – Plant Visit and talking to plant operator (J. Gascoigne, Greenfinch).
- (c) – The heat exchanger unit was remodelled in solid edge. Diameters for the pipes were estimated based on the overall dimensions of the unit. Stainless steel was assumed to be used as this was seen throughout the plant. The insulation was assumed to be Rockwool. The data for Rockwool was subsequently obtained from EcoInvent (Swiss Centre for Life Cycle Inventories 2007).
- (d) The stirring device was mainly constructed from stainless steel piping running around the plant. This was taken into account and an estimate was made on the quantity of 1" piping used. The motor and pump were accounted for elsewhere.
- (e) – Auxiliary equipment included seven 3 Phase electric motors. The dimensions were obtained from some of the manufacturers of the motors (AEG etc), along with the overall weight of the motors. A breakdown of the materials used within the motors was obtained from Mueller & Besant (1999). The pumps were divided into centrifugal and positive displacement pumps. Overall weights and dimensions for these pumps were considered to be similar to motors, however the primary material (cast iron) was accounted for.
- (f) The electrical control unit was around 0.8m in height, 0.4m in depth and around 0.7m in width. Analysis of material use for control units was carried out by EcoInvent (Swiss Centre for Life Cycle Inventories 2007) and inputted into their database. Typical breakdown of material composition for electrical control units was described to be: 46% steel, 32% plastic, 14% printed wiring board and the remaining 8% cables etc. (*ibid*). This breakdown used an estimate of 20kg for the total weight of the control unit.
- (g) The digester pre-heater used a kerosene boiler from Trainco Eurostar. The model was determined to be a Premier 100/125 condensing boiler model, which had a dry weight of 170kg. According to EcoInvent (Swiss Centre for Life Cycle Inventories 2007) typical small scale (<100kW) boilers were manufactured using a range of materials involving: 83% steel, 6% insulation (rockwool), 5% aluminium, 4% stainless steel and the remaining copper and brass. This was considered to be representative for small-scale boilers across Europe.
- (h) The digester heat was supplied using a biogas boiler by the manufacturer, Kayanson. The model used was the Hydra range. This boiler was estimated to weigh around 210kg according to manufacturer's data. The same material composition as the kerosene boiler was used.
- (i) A survey was made around the plant of the total number of nuts and bolts used (excluding the number of nuts and bolts used on the tanks themselves). This resulted in approximately 300 nuts and bolts of M10 size. The weights of these fixings were obtained from standard manufacturing data (<http://www.portlandbolt.com/bolt-weight-calculator.html>) and the material was assumed to be stainless steel.

<i>Plant Components</i>	<i>Component</i>		<i>Material</i>
Digester Tank ^(a)	Wall	25,636	kg Steel
	Insulation	623	kg Polyurethane
	Cladding	1,797	kg Steel
	Nuts, Bolts and Other	184	kg Stainless Steel
	Base (for all feedstock tanks)	182	m ³ Concrete
	Seals	25.6	kg Sealant
Digestate Tank ^(a)	Wall	52,563	kg Steel
	Nuts, Bolts and Other	310	kg Stainless Steel
	Seals	42.8	kg Sealant
Reception Tank ^(a)	Wall	9,823	kg Steel
	Nuts, Bolts and Other	83	kg Stainless Steel
	Seals	11.52	kg Sealant
Biogas Storage Tank ^(b)	Lid Weight	0.194	m ³ Concrete
	Outer Skin	80	kg Glass Reinforced Plastic (GRP)
	Base	0.75	m ³ Concrete
Heat Exchanger Unit ^(c)	External Slurry Pipe	555	kg Stainless Steel
	Slurry Pipe to Digester	472	kg Stainless Steel
	Internal Water Pipe	101	kg of Stainless Steel
	Insulation	40	m Lagging Insulation (Rockwool)
	Container	2,230	kg Steel
Stirring Device ^(d)	Piping and Valves	214	kg Stainless Steel
Auxiliary Equipment ^(e)	x7 Electric Motors	160	kg Cast Iron
		23	kg Copper
		23	kg Steel
	x3 Centrifugal Pumps	108	kg Cast Iron
	x2 Positive Displacement Pumps	41.6	kg Cast Iron
	x3 Other Pumps	21.3	kg Cast Iron
		0.3	kg Steel
		0.3	kg Steel
	Electrical Control Unit ^(f)	9	kg Steel
		6	kg Plastics
		3	kg of Printed Wiring Board
		2	kg Cables
Digester Pre-Heat ^(g)	Kerosene Boiler	9	kg Aluminium
		0.06	kg Brass
		6	kg Stainless Steel
		1	kg Plastics
		10	kg Insulation (Rockwool)
		140	kg Steel
		4	kg Copper
Digester heater ^(h)	Biogas Boiler	14	kg Aluminium
		0.09	kg Brass
		9	kg Stainless Steel
		2	kg Plastics
		15	kg Insulation (Rockwool)
		211	kg Steel
		6	kg Copper
Other Nuts and Bolts ⁽ⁱ⁾		20	kg Stainless Steel

Table B1 - List of components for AD plant manufacture - materials breakdown

Emissions to soil

The emissions to soil were obtained from the Scottish Agricultural College (SAC). The SAC had carried out a digestate examination on the plant in 2007 and the results have been shown in Table B2.

Table B2 - SAC data for digestate heavy metals composition

	Aqua regia calcium	Aqua regia magnesium	Aqua regia sodium	Aqua regia zinc	Aqua regia copper	Aqua regia iron	Aqua regia manganese	Aqua regia aluminium	Aqua regia sulphur	Water Soluble Phosphorus
	%DM	%DM	%DM	mg/kgDM	mg/kgDM	mg/kgDM	mg/kgDM	mg/kgDM	mg/kgDM	%DM
12/02/2007	7.68	2.53	0.98	166	161	2620	335	929	4860	0.012
15/02/2007	7.58	2.45	0.99	170	162	2380	351	933	5040	0.012
19/02/2007	7.53	2.39	1.05	165	149	2370	341	881	5060	0.01
22/02/2007	7.05	2.3	1.02	169	185	2340	339	855	5010	0.011
26/02/2007	7.81	2.57	1.09	173	172	2400	353	892	5160	0.011
01/03/2007	7.24	2.47	1.14	179	187	2420	355	884	5220	0.011
05/03/2007	7.5	2.63	1.17	174	195	2430	346	900	4990	0.013
08/03/2007	7.15	2.42	1.15	180	215	2270	347	879	5010	0.012
12/03/2007	5.98	2.21	0.98	126	187	1560	262	557	4010	0.012
Mean	7.28	2.44	1.06	166.89	179.22	2310.00	336.56	856.67	4928.89	0.0116
?(?·y) ²	2.40	0.14	0.05	2096.89	3277.56	704200.00	6604.22	105826.00	1033688.89	0.0000

Detailed calculations of the LCA allocation procedure

Economic Allocation

Under normal operating conditions, an anaerobic digestion plant releases biogas as a source of energy. Once the digestion process has terminated the digestate can then be distributed on farming land as a source of natural fertiliser. Dairy cattle waste is composed of 45% slurry and 55% farm yard manure (FYM) which is solid (Mistry & Misselbrook 2005). This correlated with results of studies from Williams et al. (2006) of 44:56. Due to the uncertainty of the composition of the feedstock entering the digester it was assumed that this ratio would be used in order to determine the fertiliser values of the feedstock.

By examining 1m³ of feedstock comprising of a 45:55 ratio between slurry and FYM it was determined that the following compositional values could be used as plant nutrients:

Cattle Waste	£/kg of fertiliser £	Fertiliser/m ³ slurry Kg	Fertiliser/m ³ of FYM Kg	Fertiliser/m ³ (45:55) kg	(ADAS 2007) kg	Corresponding Market Value £
N	1.07	3.5	1.7	2.5	2.9	3.10
P ₂ O ₅	1.50	1.1	2	1.6	1.08	1.62
K ₂ O	0.97	5.8	4.6	5.1	4.2	4.07

Table B3 - Market value of 1 cubic metre of cattle waste

From Table B3 the calculated total market value of a 1m³ of cattle waste was £8.79, i.e. the summation of all three fertiliser types. These market figures were obtained from 2009 data sources (Nix 2009). These three types of nutrients provide valuable natural sources of fertiliser for plants, which are both economically attractive and environmentally less burdening. In the UK alone it is reported that around £60 million per annum is saved on artificial fertiliser through the use of naturally occurring nitrogen from animal waste (Soffe 2003).

Having obtained an economic value for one of the outputs from the life cycle study, the next stage was to allocate an economic value to the second output, biogas. The biogas produced was used for three main purposes, which are as follows: biogas used for:

- Heating digester tank
- Providing energy for farm house central heating and hot water
- Providing energy for farm house cooking (Rayburn)

From the visit to the anaerobic digestion plant, it was determined that around 55% of the biogas was re-circulated back into the anaerobic digestion process in order to heat the feedstock. Less than 25% of the remaining biogas was used for hot water and central heating for the farm house. The final 20% was used for cooking and additional heating/water with a Rayburn Stove. The recorded methane quality of the biogas was between 58-64% and assuming methane content of around 35.8MJ (Ecofys 2005) the calculated heat power rating was 68 kW.

However, the actual recorded biogas required for heating the digester is a fixed 11.5m³/hr, as shown in Figure B1. This is obviously greater than the overall biogas production; however the biogas heat requirement is intermittent throughout the day and dependent on the seasonal climate.

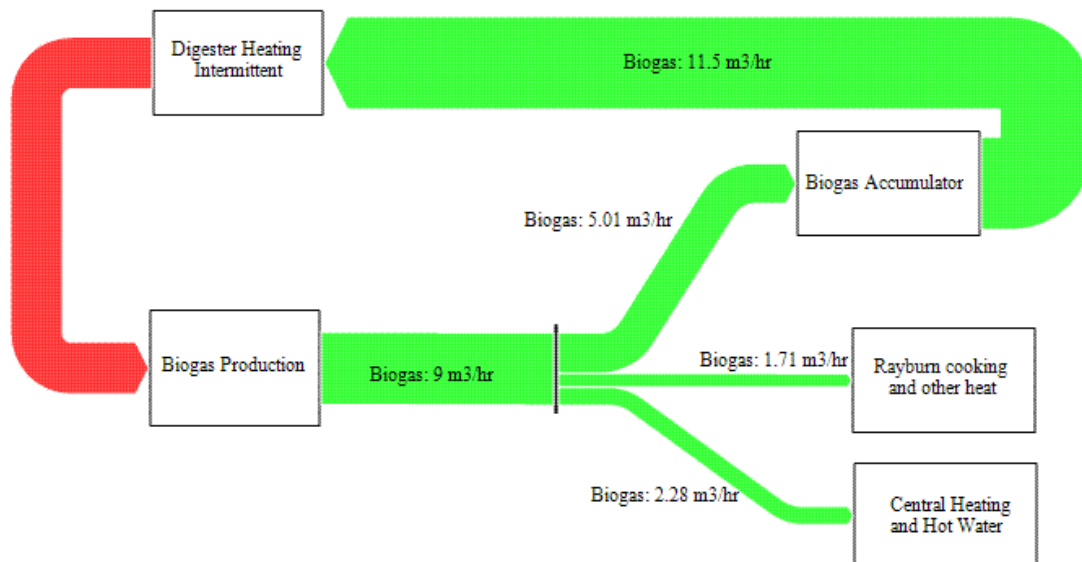


Figure B1 - Biogas flows around the plant

The total useful energy out from the biogas is delivered by the sum of the hot water, central heating and cooking biogas which equates to $3.99\text{m}^3/\text{hr}$. The remaining $5.01\text{m}^3/\text{hr}$ was required in order to obtain the original $3.99\text{m}^3/\text{hr}$ of useful energy and therefore was not considered as an output in the economic allocation. The use of biogas for domestic hot water, space heating and cooking displaces the use of an oil-burning boiler for heating water, radiators and cooking. The calculation assumed that around 17.1m^3 of biogas would be produced from 1m^3 of waste. This was calculated using a figure of $8.89\text{m}^3/\text{hr}$ of biogas for a period of 24hrs (daily waste intake $12.5\text{m}^3/\text{day}$). The calculation steps to determine the financial displacement of the biogas from the use of kerosene has been shown in Table B4. The calculation also considered a total annual waste processed of 653.2m^3 , which was used to determine total annual biogas yield.

Waste entered into digester per year	653.2	m ³	
Biogas produced from digester	17	m ³ /m ³ of waste	
Methane produced equivalent	9.86	m ³ /m ³ of waste (58% conversion)	
Methane energy (Net)	35.8 MJ/m ³		Source: (Ecofys 2005)
Kerosene energy (Net)	34.8 MJ/litre (43.61 MJ/kg)		Source: (Esso 2004)
<i>Biogas used within house (annual)</i>			
Energy demand from house	73.3	GJ/annum	
Biogas demand	3,530	m ³ /annum	
Biogas per unit input	5.40	m ³ /m ³ of waste	
Methane equivalent	3.13	m ³ /m ³ of waste	
Energy provided by biogas	112.2	MJ/m ³ of waste	
<i>Energy lost through efficiency</i>			
Gas Burner Efficiency	90%		Source: (SEDBUK 2009)
Oil Burner Efficiency	97%		Source: (SEDBUK 2009)
Cost of Kerosene 28 sec spec.	0.41	£/litre	Source: (BoilerJuice 2009)
Effective end-use energy	101.00	MJ/m ³ of waste	
Oil required energy value	104.12	MJ/m ³ of waste	
<i>Oil required</i>			
Oil required	2.99	litre/m ³ of waste	
<i>Cost of oil displacement</i>			
Cost of oil displacement	1.23	£/m ³ of waste	

Table B4 - Cost of oil displacement from biogas

The calculation's assumptions for kerosene oil price, gas and oil burner efficiencies have all been referenced accordingly. Using the above calculation steps it was determined that the cost of oil displacement for household energy consumption was approximately £1.23/m³_{waste}. The total biogas used within the farmhouse was calculated to be 4.96 m³/m³_{waste} inputted into the digester. This was achieved by taking into account the total waste per day, which was recorded to be 12.5m³/day and distributing the waste input evenly over a 24 hour period (J. Gascoigne, Greenfinch, 2008, personal communication). The domestic energy demand was determined using the BREDEM-8 model.

Mass Allocation

Mass allocation differs from economic allocation, as it utilises the physical properties of a multi-output process. This type of allocation can be applied by computing the share in physical quantity of a product. The benefit of a mass-based allocation method is that it is independent of a variable financial market. Compound fertiliser for example (N-P-K combination of fertiliser compounds) has increased significantly during 2006-2008. As shown in Figure B2, the price index compared to 2000 has increased significantly in a very short period. Therefore, results from an economic allocation could change significantly.

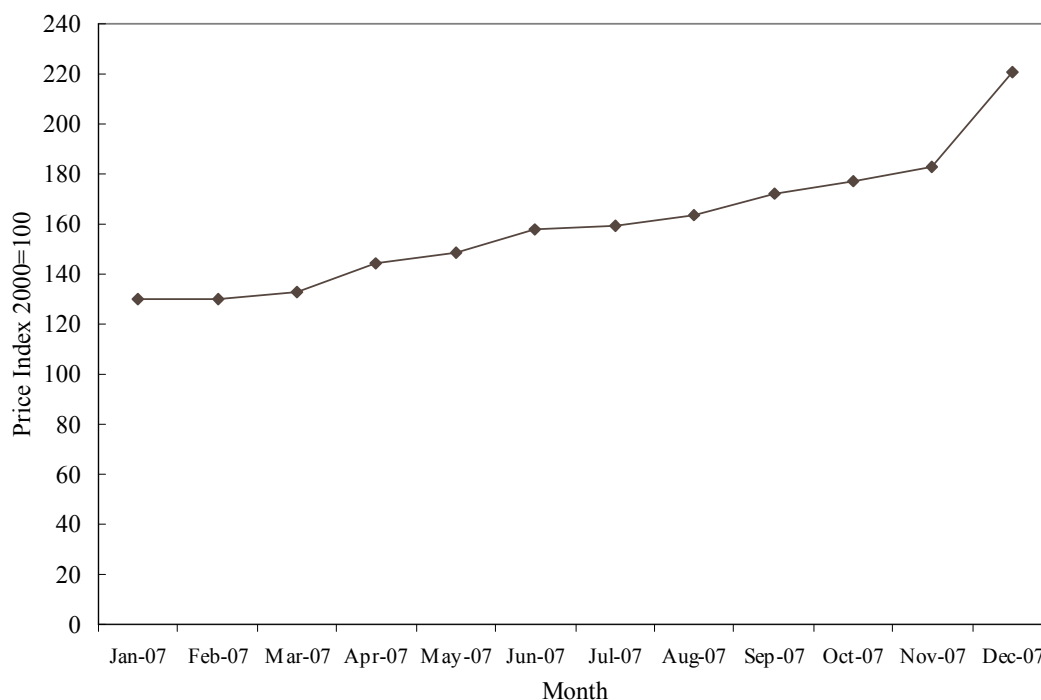


Figure B2 - Artificial fertiliser value between Jan 07-Dec 07

Mass allocation for this study examined the mass entering the system and the mass exiting for different outputs. From the mass balance shown in Table B5, it was assumed that useful biogas used for domestic purposes was just over 9m³/day; this was equated using the BREDEM-8 domestic energy consumption model for UK houses.

Raw material into digester	12,500	kg/day
	653,200	kg/annum
Biogas produced from digester	17.1	m ³ /m ³ waste
	12,487	kg/annum
Raw material out of digester	12,260	kg/day
	640,513	kg/annum
Domestic heat biogas used	10.85	kg/day
	3,961	kg/annum
1m ³ of Farm waste delivers:	2.5 kg	N Fertiliser (Nix 2009)
	1.6 kg	P ₂ O ₅ Fertiliser (Nix 2009)
	5.1 kg	K ₂ O Fertiliser (Nix 2009)
Fertiliser Available from digester	5,895	kg/annum

Table B5 - Calculation of biogas use based on mass allocation

Calculating energy demand for the domestic farm house

This section highlights the calculation procedure for determining the energy demand of the farm house. This subsequently determines the biogas demand.

Cooking energy requirement

The energy supplied for cooking within the farmhouse was delivered through the use of a Rayburn cooker. From the BREDEM-8 model, it was determined that the energy supplied from a typical gas cooker can be deduced using the current equation:

$$E_k = 2.98 + 0.6N$$

Where E_k is the fuel requirement used for cooking (GJ) and N is the number of occupants. The constants A and B are equal to 2.98 and 0.6 respectively and these values change for different fuel types. However, the constants used were for gas cooking.

The use of cooking also has an effect on the space heating requirements of a domestic property. The losses through cooking energy can be associated with the gains in the space heating energy. These energy gains appear throughout the house and will be discussed in more detail later on. However for gas cooking the energy gains experienced are equal to:

$$G_k = 70.9 + 14.3N$$

Where G_k is the energy gain from gas cooking (GJ) and N is the number of occupants. The farmhouse was also considered to have above average cooking energy consumption and therefore adopted the assumption of 20% increase on the results in accordance with the BREDEM-8 model.

Hot water energy demand

The hot water demand was based on assuming occupancy of 6 residents within the house. The determination of hot water demand was calculated using a combination of the BREDEM-8 model and work carried out by the Energy Saving Trust. The demand from the BREDEM-8 model estimated the volumetric demand (in litres) as:

$$DHW(ltrs) = 38 + 25N$$

Where N is the number of occupants. However studies from the Energy Saving Trust (EST) determined that a more suitable volumetric demand equation for a household of 5 or fewer would be (Domestic Hot Water DHW):

$$DHW(ltrs) = 40 + 28N$$

The BREDEM-8 model also assumed delivered hot water would be based on a 50°C in temperature rise, thus estimating an intake temperature of 10°C. However cold water inlet temperatures from the EST report were 15.2°C and that house with regular boilers would require

a typical hot water temperature of $52.9 \pm 1.5^\circ\text{C}$. From these results and by applying the specific heat capacity of water ($c_p = 4200\text{J/kgK}$) the energy demand can be deduced by:

$$DHW(J) = mc_p(T_1 - T_2)$$

Where T_1 is the hot water temperature and T_2 is the inlet water temperature. Upon completion of the calculation for domestic hot water the distribution losses were also taken into consideration. These losses were reported to be around 15% of the total energy use. The calculated DHW requirement using four occupancies was 188 litres of hot water per day. From this, the overall energy demand was calculated.

Space heating

Space heating energy requirements proved to be the most challenging figure to calculate. A number of aspects affect the typical space-heating requirement of a domestic property:

- Heat losses through walls, windows, doors
- Heat losses through air ventilation and occupant ventilation
- Outdoor temperature and windspeed
- Sunlight – resulting in solar gain
- Other gains

The overall simplified equation for space heating requirements for a domestic house is:

$$Q = 8.64 \times 10^{-5} d [H(T_{\text{int}} - T_{\text{ext}}) - G]$$

Following Newton's law of cooling, where:

Q is the monthly energy requirement (GJ)

d is the number of days in the month

H is the heat loss ($\text{W}/^\circ\text{C}$)

G is the heat gains (W)

T_{int} and T_{ext} are the internal and mean external temperatures of the house ($^\circ\text{C}$)

Determining T_{int} and T_{ext}

The mean external temperature of the farmhouse has been shown below with maximum and minimum temperatures per month. The average temperature demand of a domestic building was reported to be between 21°C and 18°C depending on the area of the house in the BREDEM-8 model. However the report from the Building Research Establishment (BRE) stated that for a centrally heated home the mean comfort temperature would be 21°C . The temperature requirement for this study assumed a fixed temperature of 21°C , in accordance with the BREDEM-8 model. The requirement for heat energy (neglecting gains) was shown in Figure B3.

The maximum and minimum external temperatures were obtained from the Met Office (2008) for the Aspatria weather station (closest to the farmhouse).

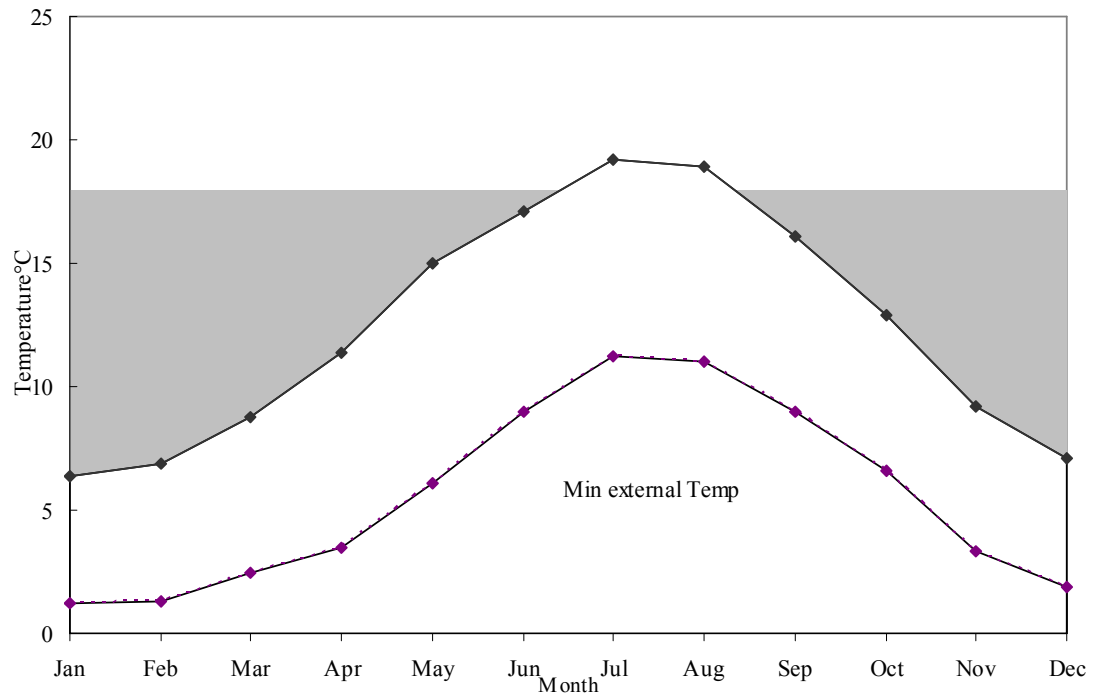


Figure B3 - Maximum and minimum ambient temperature within farm surroundings

The actual energy requirement for space heating is dependant on several factors as mentioned previously. The calculation steps for determining the gains and heat losses have also been shown below.

Space heating gains

The gains for space-heating a building can come from a number of areas these include:

- Gains from cooking
- Solar gains
- Domestic hot water gains
- Metabolic gains

These gains have an ultimate effect on the energy demand for space heating. The demand is likely to reduce the more these gains are generated. To calculate the gains for each of these factors the BREDEM-8 model uses extensive knowledge and data regarding the positioning of the house towards sunlight, the insulation material used for domestic hot water systems and so forth. Due to the scope of the present work, it was considered outside of the remit of study to pursue the calculation for overall heat gains. Consequently, an average figure was obtained from the BRE energy fact file to determine the useful heat gains from a domestic property.

The results from the calculations have been shown in Table B6.

<i>Gains (2006)</i>		
Solar	353.8	PJ/year
Metabolic	110.0	PJ/year
Cooking	52.4	PJ/year
Lights & appliances	268.8	PJ/year
Water heating	460.1	PJ/year
Total Gains	1,245.1	PJ/year
Actual useful heat gains	836.3	PJ/year
Total delivered energy UK	1,904.1	PJ/year
Household numbers (2006)	26,142,000	houses
<hr/>		
Heat gains per house	32.0	GJ/year
	87.65	MJ/day

Table B6 - Calculation of building heat gains throughout year

The difference between the total gains and useful gains considers whether the gains are of any benefit to the space-heating requirement. For example, heat wasted from domestic hot water and cooking during the summer months was not considered a useful gain. These figures obtained from the BRE Energy fact file reflect these considerations. The gains used in the BREDEM-8 model allocate gains in terms of power (W) therefore the calculated average monthly gain was 1014 W based on the result from Table B6.

Heating losses

Heating losses occur through a number of factors within a domestic property. These include heat losses through material by conduction, heat losses through ventilation and infiltration and also occupant ventilation. The typical U-values for building materials were also obtained from the BREDEM-8 model and have been detailed in the table below (Table B7).

		U-Value
Walls		W/m²°C
	Solid	0.35
	Cavity	0.35
	Timber Frame	0.35
Roof		
	Solid	0.35
	Insulation (100mm)	0.4
	Total	0.375
Windows - UPVC/Wood		
	Double glaze	2.8
	Triple glaze	2.1
	Single glaze	4.8
Windows – Metal		
	Double glaze	3.4*
	Triple glaze	2.6
	Single glaze	5.7
Solid wood door		3

Table B7 - Typical U values for building materials (* denotes material selected for study)

A schematic of the house was re-created using a 3D modelling package (SketchUp). The schematic below shows how the building was recreated in 3D to determine the overall wall area, window area and door and roof areas. The rear of the house was considered symmetrical to the front in terms of windows and door. Standard U-values and thicknesses for materials were obtained from the BREDEM-8 model. From the model, the following dimensions were determined. These dimensions were considered adequate for an average 4-5 bedroom detached house. The total heat loss calculated was $203.58 \text{ W/}^\circ\text{C}$. This value was then incorporated into the overall heat energy demand calculation.



Figure B4 - Schematic design for sizing of domestic heat demand

Total energy (and biogas) demand for the farm house

The overall heat energy demand was calculated for cooking energy, domestic hot water and space heating. Table B8 shows the results from the calculations. The assumptions made for cooking included house occupancy of four and that the energy used would be derived from gas. The total domestic hot water was calculated to be around 188 litres per day demand. This equated to approximately 36.3 MJ/day of hot water demand, taking into account a 15% distribution loss within the system.

Total Energy Demand for House			
Space Heating	142.74	MJ/day	
Hot Water	36.3	MJ/day	
Cooking	21.63	MJ/day	
Total	200.69	MJ/day	
	73.3	GJ/annum	
<hr/>			
Biogas Required	8.88	m ³ /day	
	3241.2	m ³ /annum	

Table B8 - Total annual biogas demand for domestic uses

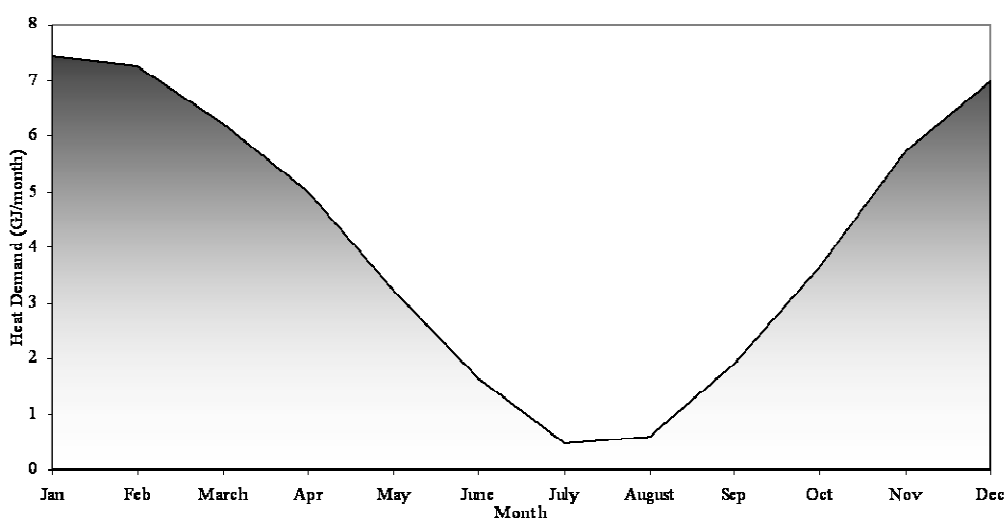


Figure B5 - Domestic heat demand throughout the year

The demand for space heating took into account the variability throughout the year as a result of the change in external temperatures. These were obtained using standard data for the area of interest (Met Office 2008). A graph showing the distribution of heat energy demand for the house has been shown in Figure B5. The calculations assumed a constant energy gain of 87.65MJ/day and an overall heat loss of 203.58 W/°C. Using these figures, the overall monthly heat energy demand was calculated. The figure was converted to an annual total then a daily total in order to obtain a mean daily heat energy demand.

As shown in Figure B5 it appears that there is an energy demand for space heating even in the summer months. This is because mean external temperatures were used. The total calculated energy demand was approximately 200.69 MJ/day. This was slightly higher than the average domestic dwelling, recorded to be around 172MJ/day (BERR 2008a).

APPENDIX C

UNDERSTANDING ENVIRONMENTAL ISSUES AND A BACKGROUND TO LIFE CYCLE
IMPACT ASSESSMENT*Explaining Environmental issues*

This section outlines the environmental effects considered in Eco-Indicator 99 (E199).

Carcinogenic effects

These effects are caused by any substance which can increase the chance of human cancer. The severity of different exposures and emissions of carcinogenic effects has been grouped into several categories by the International Agency for Research on Cancer (IARC). The groups categorise the emissions into those with the highest probability of cancer to the emissions with the lowest probability. The deadliest group (Group 1) include asbestos, benzene, cadmium, chromium and phosphorus, amongst many others. These are considered single source emissions. However, mixtures, which are also considered as having a high impact towards the risk of cancer, include household combustion of coal, wood dust, aluminium and steel production, rubber industry and tobacco smoking, amongst many others (IARC 2009).

Biogas production plants often require special treatments and coatings on the inside walls of tanks. If coatings containing cadmium, nickel or chromium are used then this could significantly increase the risks of carcinogenic emissions. Additionally the high use of stainless steel in piping containing chromium also has a high potential towards this environmental damage.

Respiratory effects

Respiratory effects can be classified into two groups; organic and inorganic. Respiratory organic effects tend to result from summer smog and cause difficulties to the human respiratory system. The pollutants are generally caused from combustion of various fuels, such as diesel and coal. In this situation the sunlight reacts with the pollutants to cause ozone, thus affecting human respiratory effects.

Respiratory inorganics result from winter smog caused by dust, sulphur and nitrogen oxides in the air (Goedkoop et al. 2008). The pollutants are generally the same as summer smog, however due to climatic temperatures, these pollutants act differently. During cold temperatures, these pollutants remain relatively close to the ground and if there are limited wind speeds, the concentration is increased significantly. The pollutants of winter smog can cause severe respiratory effects. These respiratory effects can lead to illnesses such as asthma, chest infections, bronchitis and other types of chronic obstructive pulmonary disorders. Although some of these are significantly affected by smoking, inhalation of fumes (such as fuel combustion) can also lead to these health effects.

Overall, there are a number of critical substances which cause respiratory effects including: emissions from particulates (found in dust emitting mining and combustion of diesel), nitrate and sulphate, sulphur and nitrogen oxides and carbon monoxides (Goedkoop & Spriensma 2001). The combustion of biogas is similar to the combustion of fossilised natural gas. This can lead to emissions such as sulphur dioxide and nitrogen oxides, whilst combustion of diesel could lead to

particulate emissions. The production and use of biogas is expected to have significant effects on respiratory damages due to the high level of combustion during production and use of biogas.

Climate Change

Increased man-made greenhouse gas emissions enhance sun-radiation, causing average, global ambient temperatures to rise. Climate change is probably one of the most recognized and discussed environmental concerns in recent years through the Kyoto Protocol, as discussed in Chapter 1. However, this environmental concern is of equal importance to other environmental impacts. Additionally, although global temperatures are rising, the cause has not yet been established (McManus 2001).

Climate change can cause unfavourable effects on ecosystem health and human health (Goedkoop et al. 2008). It can be affected by a number of greenhouse gases of which the most commonly known include carbon dioxide (CO₂) and methane (CH₄). The potential effects of climate change have been discussed in Chapter 1. Damage from climate change is not as direct and instantaneous as other environmental issues and present emissions are likely to create damage for future years. Therefore, damage from climate change is usually modelled through the use of scenarios (Goedkoop & Spriensma 2001).

The overall cause of climate change is known as global warming. The expected impacts of global warming are a gradual glacial retreat, where the global mass of ice is gradually reduced. This in turn will raise sea levels, receding coastal lines. Geographical regions already receiving high solar radiation could experience even higher peak ambient temperatures possibly leading to the resident population experiencing sun-stroke and dehydration (Poumadère et al. 2005). These are some of the potential implications of global warming however, the total damage to ecosystems and human health is difficult to concretise.

One of the primary goals for adopting an alternative energy source such as biogas is to reduce the potential of climate change by lowering the CO₂ and CH₄ emissions entering the atmosphere. Through the natural carbon cycle of biomass, CO₂ emissions should in theory be greatly reduced when energy is produced in this form. The LCA will be critical in determining whether a net CO₂ reduction is actually feasible through the production and use of biogas. If the process emits more CO₂ than it consumes then the benefits of this energy source should be questioned.

Radiation

Radiation damage is caused by radioactive compounds emitting radiation into living organisms. Radiation is categorised into two forms: ionizing and non-ionizing. Non-ionizing radiation (electromagnetic radiation) does not pose a health risk as it is not mutagenic. Ionizing radiation however, which includes alpha, beta, gamma and ultra violet (UV) is mutagenic. This type of radiation affects cells within living organisms. Increased exposure to radiation is linked to cancer, tumours and other genetic damage (Goedkoop & Spriensma 2001).

There are a number of materials such as iodine, uranium, caesium, cobalt and lead which emit radiation and thus are harmful to human health and ecosystems. However, within standard manufacturing processes of metals, these materials are not present and therefore the manufacturing of a biogas plant should not increase the risk of radiation. However, increased use of lead either through electronic circuit boards or electrical wire soldering could lead to over exposure of radiation emitting particles. If an LCA study were to be undertaken on nuclear

energy production, this impact category would be the one with highest impact. However, the LCIA methodology EI99 does not consider the potential impact of large leaks of radiation (Goedkoop et al. 2008).

Ozone layer depletion

The depletion of the ozone layer is caused by the emission of chloride and bromide-containing halocarbons; the most common of which is chlorofluorocarbon (CFC). The emissions react with the sunlight and destroy the ozone. The ozone layer prevents harmful radiation from the sun, such as UV, entering the earth's atmosphere. As mentioned in the previous section, UV radiation is mutagenic and can cause cancer. However, other impacts include detrimental effects on terrestrial and aquatic ecosystems and organic materials.

Ozone layer depletion can therefore affect human health and ecosystem quality. Refrigerant materials used in cooling, dehumidification and refrigeration units use substances such as HCFC gases which can cause ozone depletion. The use of ozone depleting gases during the production of biogas is not expected to be significant. However, as an important environmental concern, capable of impacting human health and ecosystem damage, this impact was examined in the LCA.

Ecotoxicity

This impact involves substances which are toxic to organisms in a way that affects the functioning and structure of the ecosystem. An ecosystem is a biological community within a specific area affected by the physical elements of its environment. Toxic substances such as cadmium, lead, copper and zinc all contribute to toxic stress when presented to ecosystems. These can be delivered through water, soil and air. They subsequently have detrimental effects on the ecosystem quality and ultimately the population of organisms which are affected (or depleted) by the exposure.

The damage from ecotoxicity could be significant within biogas production, through the use of chromium and nickel within the manufacturing processes of the plant. These are commonly used to make stainless steel and nickel-alloy coatings on manufactured components. However, during the production of biogas plant a range of plastic and rubber materials are used. These materials may have benzene as an additive, which in turn is a carcinogen. Benzene has significant health risks and its toxicity can lead to bone marrow damage and affect the immune system.

Acidification

This is degradation of ecosystems (aquatic and terrestrial) due to an increase in acid (nitric acid and sulphuric acid) concentration in soil and water. The emissions of nitrous oxides and sulphur dioxides are responsible for the increased acidity within rainwater, subsequently creating acid rain. These emissions are predominantly released during the combustion of fossil fuels; however, combustion of some biomass fuels can also produce these emissions. Catalytic converters installed on modern vehicles are able to eliminate these emissions. However, in the aviation industry these emissions cannot be reduced via catalysis, as there is no system in place similar to that of a catalytic converter for road vehicles. Acidification leads to detrimental effects especially on conifers (Sonnemann et al. 2003), whilst acidification in water systems is extremely harmful to fish. Acidification is also detrimental towards building materials, metals and surface coatings.

Eutrophication

This effect is a result of an increased concentration of nutrients; phosphorus, nitrogen and other nutrients, in a specific area. This commonly takes place in water systems such as lakes, rivers, bathing waters etc. where nutrients have either leaked or have been disposed into these systems. The increase in nutrient availability increases the growth of aquatic plants and algae. An overproduction of algae and blooms causes an increase of plant life on the water surface, which can lead to reduced sunlight and oxygen penetrating the top layer of water. This will ultimately have adverse effects on aquatic life, which requires both of these resources.

Land-use

This is a change in the use of a particular land area. An example would be the conversion of grass pastureland into industrial land use. This change would have an impact on a number of aspects. Firstly, species which use the pastureland for either shelter or feed would no longer have access. Secondly, the conversion into industrial land could also have detrimental local environmental effects due to an increase in industrial materials present on the land itself. However, this would depend highly on the type of industrial application.

Natural (non-industrialised) land can accommodate a vast number of ecosystems and wildlife species. Changing the land-use drastically affects the biodiversity of the land and subsequently the ecosystem quality. Land quality has been monitored by scientists for a number of years. Land-use quality is often scaled by the number of species and the diversity per type of land. Damage to land-use or changes of the land have a detrimental effect on the species biodiversity, which can take many years to recover.

An example of potentially detrimental land-use is the plantation of monocultures for biomass growth. These monocultures can attract and deter particular species depending on whether the monoculture meets the requirements of the species. Plantations such as miscanthus and SRC, which are cropped on a large scale, can lead to a dramatic reduction in shelter and food availability for species living within these plantations. If the land were used as unmanaged woodland, these negative effects on species and other plantations would not be observed.

Minerals

This is a measure of the rate of depletion of non-renewable resources. This has a negative affect as it reduces the availability of these resources, which humans are dependent on. These minerals include all metal types, sand, gravel and lime. The concentration of these minerals will decrease as extraction continues. This is due to a greater extraction rate than the production rate. This distribution is known as lognormal and is commonly supported amongst resource geologists (Geodkoop et al. 2008).

Fossil Resources

This environmental impact is similar to mineral resource depletion, however it accounts for all fossilised resource types. This includes crude oil, natural gas and coal. These fossil fuels can either be used for energy purposes or material production such as polymers, tars, fertilisers and solvents etc. Fossilised resources, which are not used for energy, account for 16% of total extraction.

Due to the uncertainty of fossil resource availability, it is difficult to predict or estimate the damage of this depleting resource. An accepted method used within some LCAs is to assume that

for each unit of fossil resource mined, an increase in extraction energy would be required to extract future fossil resources. The effect of this resource is measured by the relationship between the increased extraction and the increase in energy required to extract future supplies. This is defined as the difference between current resource extraction energy and energy requirement at some future point (Geodkoop et al. 2008).

Ultimately, a higher energy requirement in mineral and fossil resource extraction will lead to increased global prices of these commodities. If these commodities become too expensive, alternatives will be found at a lower cost. However, these commodities are extremely important globally. A damage or decrease in availability of these resources could have severe detrimental impacts globally.

Background of the chosen LCIA methodology (EI99)

A brief appreciation of four of the most common impact assessment methodologies commercially available has been made. There are many more LCIA methodologies which are available. Further information can be found from referenced reports associated to each methodology.

CML methodologies (mid-point) – The CML methodology was one of the first LCIA methodologies publically available, launched in 1992. The methodology was created by the 'Centre for Environmental Studies', University of Leiden. It has now been updated to CML 2001 (Guinée 2002). The method uses a problem orientated approach (mid-point analysis). The normalisation is carried out by multiplying the characterisation factor by the relevant emissions. A summation of these results for each impact category then gives the normalised data.

EPS 2000 (end-point) – The methodology analyzes five impact categories: human health, ecosystem production capacity, abiotic stock resource, biodiversity and cultural and recreational values. The methodology is able to characterise, damage assess and evaluate the environmental impact categories. The evaluation stage is carried out by applying weighting factors. These are factors represent the willingness to pay to avoid environmental changes. The creators of this methodology are Chalmers University of Technology, Centre for Environmental Assessment of Products and Material Systems (Steen 1999).

Eco-Indicator 95 (mid-point) – The creators (Pré consultants) of Eco-Indicator, released two methodologies, called Eco-Indicator 95 and Eco-Indicator 99 (denoted as EI95 and EI99). EI95 is a mid-point approach methodology; however, it does have a basic weighting procedure incorporated. The characterisation stage characterises the impacts by representing them as equivalence towards a standard unit impact. For example, all greenhouse gases are converted into kg of CO₂ equivalence, with CO₂ having a value of 1kg. The normalisation stage is carried out by comparing each impact category to the average European effect of each impact category. This is done by dividing the emissions from the process by the average European emissions per capita (Goedkoop 1995).

Eco-Indicator 99 (end-point) – This method analyses the impacts towards the end-point, thus assessing the damages of the impacts. This is done through the weighting procedure of which the first stage is carried out when creating the methodology. The normalisation stage is similar to that of EI95. However as the units of the characterisation stages are different, they measure the damage as opposed to the emission; the damage from the process is compared to the average

European damage per capita for each process. The methodology was created by the Dutch Pré consultants (Steen 1999).

The creation of EI99

There are a wide range of Life Cycle Impact Assessment (LCIA) databases available which can be used to model the impacts of a given inventory of results. The LCIA stage assists “the understanding of the Life Cycle Inventory (LCI) results, making these results more manageable in relation to the natural environment, human health, and resources and may identify the relative significance of the LCI results” quoted from the ISO standards for LCA.

Eco-Indicator 99 is a Life Cycle Impact Assessment (LCIA) methodology. This has been used for the research carried out. The methodology was created using a “top down” approach as opposed to a “bottom up” approach. This meant that instead of starting with the emissions from the inventory and examining the environmental impacts, the reverse was adopted. Traditional LCIA methodologies examined the environmental impacts starting from the product system. However, the top-down approach starts with the ‘end-goal’ of the LCA. This alternative methodology determines: what the aim of the LCA is; what are the environmental impacts and what are the

ts which should be reduced; which type of environmental interventions cause the impacts. This methodology starts by looking at the inventory data and emissions associated with the inventory. Subsequent to this the effect of the emissions on the environment are examined. The Eco-Indicator 99 methodology was carried out starting with the weighting procedure. This was done in order to remove or reduce the ambiguity in the final weighting stage.

The weighting stage was carried by a panel of LCA experts and users. The creators of Eco-Indicator 99 decided that an effective way of obtaining information from the panel was to have the least possible number of damages caused by various impact categories and not to ask the panel to weight the impact categories themselves. The overall objectives of questioning the panel were to:

- Items should not be too abstract and therefore easy to understand.
- Number of items should be limited to as few as possible.
- Items should include all relevant environmental effects.

The weighting procedure was carried out through a questionnaire sent to 365 Swiss LCA experts and users. 85 responded, of which only 45 result sets were used. The panel members were asked to weight three damage categories: human health, ecosystem quality and resource. These were considered to incorporate all relevant environmental effects. The results of the weighting have been shown in Table C1.

	Mean	Rounded	St. Deviation	Weighting Allocated
Human Health	36%	40%	19%	400
Ecosystem Quality	43%	40%	20%	400
Resources	21%	20%	14%	200

Table C1 -Valuation of the three damage categories

The results from the expert panel showed that ecosystem quality and human health were given the same importance, whilst resource was given half importance. The panel was then asked a

series of questions regarding attitudes and perspectives of society. Based on these results the respondents could be grouped into three different archetypes. The three groups were addressed to deal with the uncertainty of the results. The three perspectives were as follows: Hierarchist, Individualist and Egalitarian. These have been summarised in Table C2.

Perspective	Time view	Manageability	Level of evidence
Hierarchist	Balance between short and long term	Proper policy can avoid many problems	Inclusion based on consensus
Individualist	Short time	Technology can avoid many problems	Only proven effects
Egalitarian	Very long term	Problems can lead to catastrophe	All possible effects

Table C2 - Three archetypes used to model life cycle assessment within EI99

These three archetypes have been attained from the cultural theory framework (Hofstetter 1998), which are commonly used within social science. From these results, three versions of Eco-Indicator 99 were created based on the perspective choices.

The creation of Eco-Indicator 99 methodology can be grouped into three steps. These three steps are also the inverse process of the LCIA methodology set-out by the standard procedure (British Standards 2006). These three steps include:

1. Weighting Stage
2. Creating the damage models
3. Creating an Inventory of the processes

Weighting Stage (Stage 1)

The aim of this stage was to weight the damage categories initially. The damage categories were chosen based on the criteria that they had to be: as few as possible, easy to understand and cover all relevant environmental effects.

Creating the damage models (Stage 2)

In order to assign a value to each damage category, damage models were created. The damage models are required to link the damage categories with the inventory results. Figure C1 represents how the damage models link the inventory results to the damage categories.

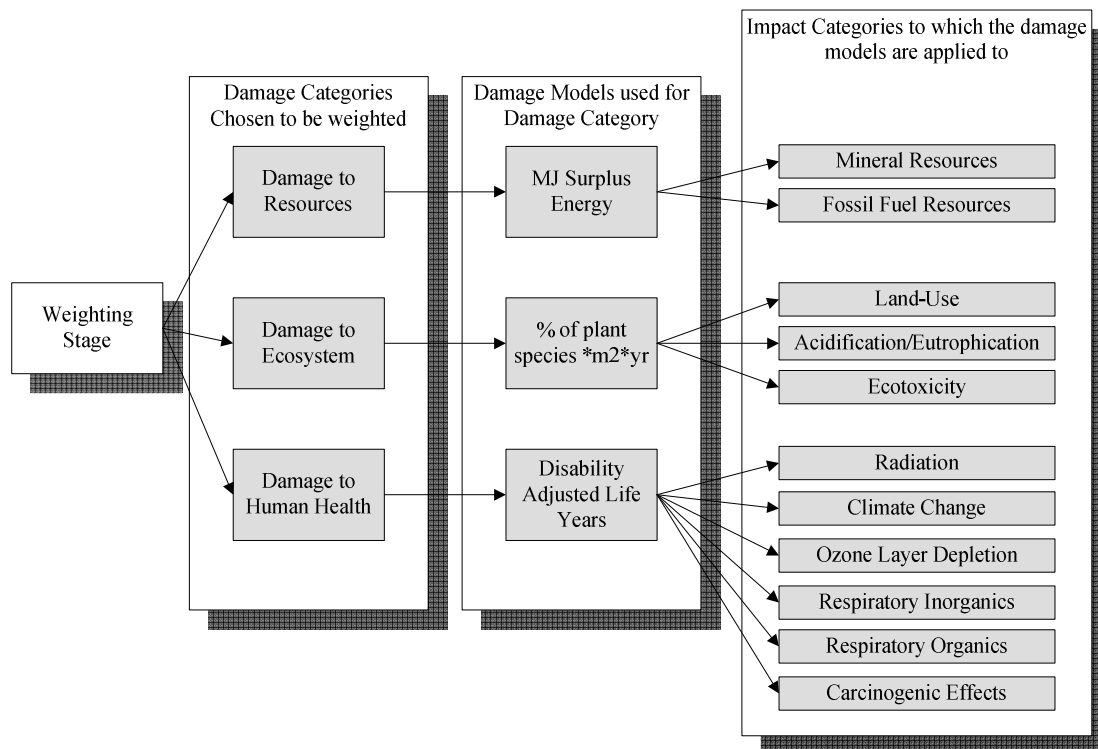


Figure C1 - The creation process of EI99

Damage model for emissions

In general, damage models were created for three main areas: emissions, land-use and resources. The methodology for creating emission damage models was the same regardless of the impact category which was chosen. The emission damage model was created using:

Fate analysis – The fate analysis examines the behaviour of a chemical substance during its lifetime and how the chemical behaves when it is released into the environment, assessing the behaviour of the chemical and the degradation of the substance in an environment. The concentration in air, water, soil and food can then be examined.

Exposure analysis – Taking the results calculated of the concentration of a substance, the next stage is to determine how much of the substance will be received by humans, plants and other life forms.

Effect analysis - Once the exposure is determined the next stage is to determine the types of diseases and the frequencies at which these may occur.

Damage analysis – This stage examines how many years of life lost or disabled a certain disease causes and the criticality of the disease. However this can only be applied to human health. For ecosystems quality, another procedure must be undertaken. For ecotoxicity modelling, the percentage of plants and species which are exposed to toxic stress are calculated (Potentially Affected Fraction PAF). For acidification and eutrophication the percentage of plants which are likely to disappear is calculated (Potentially Disappeared Fraction PDF). These damages are modelled to European scale. However, more researched effects such as green-house gases, ozone layer depleting substances etc. are calculated using world-wide data.

Damage model for land-use

The unit taken for this damage is the disappearance of species. The methodology developed a scale to express the species diversity per type of land use. This methodology is able to model the percentage of disappearance of species depending on the land use.

Damage model for resources

For minerals it was observed that when these are extracted initially, eventually it will be more difficult (energy intensive) to find others and the quality will also be of lower grade. Therefore for this impact category the damage to the resource will be experienced by future generations as more resources will be needed to extract the remaining resource. Therefore this is expressed as surplus energy; a measure of the predicted future energy required for extracting resources.

Fossil fuel extraction operates on a similar level, however the concentration will not vary as it does with minerals. The research carried out in this field clearly indicates that easily accessible fossil fuels are in decline. Therefore based on this assumption, more energy will be needed to extract future resources. This is therefore also measured as surplus energy (MJ).

Inventory of the processes (Stage 3)

Once the damage models were created, the inventory processes to which the damage models could be allocated towards were subsequently determined. This inventory was then able to have a damage factor assigned to it. This is the final stage of the Eco-Indicator 99 creation. The Eco-Indicator methodology was based on the energy database developed by ESU-ETH in Zurich. The creators of the Eco-Indicator tool warn not to mix databases with indicators that have been developed with different methodologies.

Normalisation stage in EI99

The following stage of the LCIA is the normalisation step. The normalisation technique enables all the impact categories to become dimensionless. The reference system chosen is based on European normalisation values. For the case of EI99, the normalisation factors were calculated using two steps:

1. Finding the total emissions and resource consumption caused by the reference system during a reference period (a year usually).
2. Calculating the impact categories and if applicable, the damage scores, using the characterisation and damage factors. This value is then divided by the number of inhabitants.

The normalisation figures are calculated using published data based on European emissions. The theory adopted to determine the European emissions assumes that the industrial structure and therefore the emission pattern are represented well by the energy use in the country (Goedecke & Spriensma 2001). To determine the total European emissions the formula:

$$E_i = P_i \left(\frac{E_K}{P_K} \right)$$

Where E_t is the total emissions in Europe, P_t is the total energy use in Europe, P_K is the energy use of countries with known emissions and finally E_K is the known emissions (Goedecke & Spriensma 2001). The emissions are then grouped into the categories stated by Eco-Indicator 99 methodology and the damage factor for each emission is then applied. This gives a result for the total European emissions for each substance under each Impact Category in units of DALY, PAF*m2*yr and MJ.

The total European emissions for each category are then combined to give a total for the three different damage categories (human health, ecosystem quality and resource damage). These values are then divided by the total European inhabitants to determine a specific European emission value. The results for the three different perspectives (egalitarian, hierarchist and individualist) have been shown in Table C3. The inverse of the total per inhabitant is then multiplied by the calculated characterized value. This manipulation makes the value dimensionless and therefore enables the 11 Impact categories to be compared.

	Unit	Total	Per Inhabitant	Inverse per Inhabitant
Egalitarian				
<i>Human Health</i>	DALY/yr	5.88E+06	1.55E-02	6.45E+01
<i>Ecosystem Quality</i>	PDFm ² yr/yr	1.95E+12	5.13E+03	1.95E-04
<i>Resource Damage</i>	MJ/yr	2.26E+12	5.94E+03	1.68E-04
Hierarchist				
<i>Human Health</i>	DALY/yr	5.84E+06	1.54E-02	6.49E+01
<i>Ecosystem Quality</i>	PDFm ² yr/yr	1.95E+12	5.13E+03	1.95E-04
<i>Resource Damage</i>	MJ/yr	3.20E+12	8.41E+03	1.19E-04
Individualist				
<i>Human Health</i>	DALY/yr	3.13E+06	8.25E-03	1.21E+02
<i>Ecosystem Quality</i>	PDFm ² yr/yr	1.71E+12	4.51E+03	2.22E-04
<i>Resource Damage</i>	MJ/yr	5.61E+10	1.50E-03	6.67E+02

Table C3 - Normalised data from EI99 methodology

Damage factors used in Eco-Indicator 99

The following pages are obtained from the methodology report for Eco-Indicator 99. These show the damage factors used within the methodology. These factors form the basis of the calculations for the characterised and normalised data within the LCA. The full report can be obtained from the Pre website: http://www.pre.nl/download/EI99_methodology_v3.pdf

1 Damage factors in the hierarchist perspective (default) (H,A)

This annex lists the Eco-indicator 99 damage factors for the substance lists that can be found in most popular LCA databases. In this case the hierarchist perspective is used, combined with the default (average) weighting factors. Next to the damage factors two columns are added with the normalised and weighted damages. The normalisation factors and the weights are specified below:

	Normalisation	Weights
Human Health	1.54E-02	400
Ecosystem Quality	5.13E+03	400
Resources	8.41E+03	200

Below the impact categories are listed per damage category.

1.1 Damage category Human Health (H,A)

The human health damages are specified in DALYs. This is short for Disability Adjusted Life Years. A damage of 1 means one life year of one individual is lost, or one person suffers four year from a disability with a weight of 0.25.

1.1.1 Carcinogenic effects on humans (H,A)

For the fate and exposure it is important to distinguish emissions to soil between emissions in industrial (ind.) or agricultural (agr.) soil. All emissions of pesticides are assumed to occur in agricultural soil, all other emissions are assumed to occur in industrial (or urban) soil. No direct emissions are assumed to occur in natural soil.

Fate factors are calculated with EUSES. Substances from IARC substances groups 1, 2a and 2b are included.

All damage factors are expressed per kg emission. The unit of damage is DALYs.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	1,2-dibromoethane	2.60E-04	1.69E-02	6.75E+00
Air	1,2-dichloroethane	2.98E-05	1.94E-03	7.74E-01
Air	1,3-butadiene	1.58E-05	1.03E-03	4.10E-01
Air	1,4-dioxane	1.39E-07	9.03E-06	3.61E-03
Air	2,4,6-trichlorophenol	2.05E-06	1.33E-04	5.32E-02
Air	acetaldehyde	2.16E-07	1.40E-05	5.61E-03
Air	acrylonitrile	1.69E-05	1.10E-03	4.39E-01
Air	alpha-hexachlorocyclohexan	3.00E-04	1.95E-02	7.79E+00
Air	Arsenic	2.46E-02	1.60E+00	6.39E+02
Air	Bis(chloromethyl)ether	7.48E-03	4.86E-01	1.94E+02
Air	benzene	2.50E-06	1.62E-04	6.49E-02
Air	benzo(a)anthracene	5.86E-02	3.81E+00	1.52E+03
Air	benzo(a)pyrene	3.98E-03	2.58E-01	1.03E+02
Air	benzotrichloride	6.60E-03	4.29E-01	1.71E+02
Air	benzylchloride	1.04E-05	6.75E-04	2.70E-01
Air	beta-chlorocyclohexan	9.99E-05	6.49E-03	2.59E+00
Air	bromodichloromethane	8.76E-06	5.69E-04	2.28E-01
Air	Cadmium	1.35E-01	8.77E+00	3.51E+03
Air	Chromium (VI)	1.75	1.14E+02	4.55E+04
Air	di(2-ethylhexyl)phthalate	3.38E-05	2.19E-03	8.78E-01
Air	dibenz(a)anthracene	3.10E+01	2.01E+03	8.05E+05
Air	dichloromethane	4.36E-07	2.83E-05	1.13E-02
Air	Dichlorvos	3.15E-05	2.05E-03	8.18E-01
Air	2,3,7,8-TCDD Dioxin	1.79E+02	1.16E+04	4.65E+06
Air	epichlorohydrin	3.02E-07	1.96E-05	7.84E-03
Air	ethylene oxide	1.83E-04	1.19E-02	4.75E+00

Air	formaldehyde	9.91E-07	6.44E-05	2.57E-02
Air	gamma-HCH (Lindane)	3.49E-04	2.27E-02	9.06E+00
Air	Hexachlorobenzene	8.25E-02	5.36E+00	2.14E+03
Air	metals	5.20E-03	3.38E-01	1.35E+02
Air	Nickel	2.35E-02	1.53E+00	6.10E+02
Air	Nickel-refinery-dust	4.74E-02	3.08E+00	1.23E+03
Air	Nickel-subsulfide	9.48E-02	6.16E+00	2.46E+03
Air	PAH's	1.70E-04	1.10E-02	4.42E+00
Air	particles diesel soot	9.78E-06	6.35E-04	2.54E-01
Air	Polychlorobiphenyls	1.97E-03	1.28E-01	5.12E+01
Air	pentachlorophenol	7.21E-03	4.68E-01	1.87E+02
Air	propyleneoxide	1.17E-05	7.60E-04	3.04E-01
Air	styrene	2.44E-08	1.58E-06	6.34E-04
Air	perchloroethylene	4.82E-07	3.13E-05	1.25E-02
Air	carbontetrachloride	8.38E-04	5.44E-02	2.18E+01
Air	chloroform	2.63E-05	1.71E-03	6.83E-01
Air	vinyl chloride	2.09E-07	1.36E-05	5.43E-03
Water	1,2-dibromoethane	1.24E-03	8.05E-02	3.22E+01
Water	1,2-dichloroethane	2.98E-05	1.94E-03	7.74E-01
Water	1,3-butadiene	3.37E-04	2.19E-02	8.75E+00
Water	1,4-dioxane	9.21E-07	5.98E-05	2.39E-02
Water	2,4,6-trichlorophenol	1.05E-05	6.82E-04	2.73E-01
Water	acetaldehyde	9.23E-07	5.99E-05	2.40E-02
Water	acrylonitrile	4.16E-05	2.70E-03	1.08E+00
Water	alpha-hexachlorocyclohexan	6.85E-03	4.45E-01	1.78E+02
Water	Arsenic	6.57E-02	4.27E+00	1.71E+03
Water	Bis(chloromethyl)ether	1.54E-02	1.00E+00	4.00E+02
Water	benzene	4.12E-06	2.68E-04	1.07E-01
Water	benzo(a)anthracene	6.58E-01	4.27E+01	1.71E+04
Water	benzo(a)pyrene	2.99	1.94E+02	7.77E+04
Water	benzotrichloride	9.46E-03	6.14E-01	2.46E+02
Water	benzylchloride	1.98E-05	1.29E-03	5.14E-01
Water	beta-chlorocyclohexan	5.75E-03	3.73E-01	1.49E+02
Water	bromodichloromethane	9.36E-06	6.08E-04	2.43E-01
Water	Cadmium	7.12E-02	4.62E+00	1.85E+03
Water	Chromium (VI)	3.43E-01	2.23E+01	8.91E+03
Water	di(2-ethylhexyl)phthalate	6.64E-04	4.31E-02	1.72E+01
Water	dibenz(a)anthracene	4.07E+01	2.64E+03	1.06E+06
Water	dichloromethane	4.97E-07	3.23E-05	1.29E-02
Water	Dichlorvos	1.17E-05	7.60E-04	3.04E-01
Water	dioxins (TEQ)	2.02E+03	1.31E+05	5.25E+07
Water	epichlorohydrin	9.90E-07	6.43E-05	2.57E-02
Water	ethylene oxide	1.39E-04	9.03E-03	3.61E+00
Water	formaldehyde	4.97E-06	3.23E-04	1.29E-01
Water	gamma-HCH (Lindane)	4.16E-03	2.70E-01	1.08E+02
Water	hexachlorobenzene	1.25E-01	8.12E+00	3.25E+03
Water	Nickel	3.11E-02	2.02E+00	8.08E+02
Water	Nickel-subsulfide	5.02E-03	3.26E-01	1.30E+02
Water	Nickel-refinery-dust	1.00E-02	6.49E-01	2.60E+02
Water	PAH's	2.60E-03	1.69E-01	6.75E+01
Water	Polychlorobiphenyls	3.91E-02	2.54E+00	1.02E+03
Water	pentachlorophenol	2.29E-02	1.49E+00	5.95E+02
Water	propylene oxide	1.74E-05	1.13E-03	4.52E-01
Water	styrene	1.22E-06	7.92E-05	3.17E-02
Water	perchloroethylene	4.72E-07	3.06E-05	1.23E-02
Water	carbontetrachloride	8.29E-04	5.38E-02	2.15E+01
Water	chloroform	2.60E-05	1.69E-03	6.75E-01
Water	vinyl chloride	2.84E-07	1.84E-05	7.38E-03
Soil	1,2-dibromoethane (ind.)	3.81E-03	2.47E-01	9.90E+01
Soil	1,2-dichloroethane (ind.)	4.58E-04	2.97E-02	1.19E+01
Soil	1,3-butadiene (ind.)	1.20E-05	7.79E-04	3.12E-01
Soil	1,4-dioxane (ind.)	3.10E-07	2.01E-05	8.05E-03
Soil	2,4,6-trichlorophenol (ind.)	2.76E-06	1.79E-04	7.17E-02
Soil	acetaldehyde (ind.)	4.77E-07	3.10E-05	1.24E-02
Soil	acrylonitrile (ind.)	7.01E-05	4.55E-03	1.82E+00
Soil	alpha-hexachlorocyclohexan (agr.)	2.32E-02	1.51E+00	6.03E+02
Soil	Arsenic (ind.)	1.32E-02	8.57E-01	3.43E+02
Soil	Bis(chloromethyl)ether (ind.)	1.68E-02	1.09E+00	4.36E+02
Soil	benzene (ind.)	1.33E-05	8.64E-04	3.45E-01
Soil	benzo(a)anthracene (ind.)	1.60E-01	1.04E+01	4.16E+03
Soil	benzo(a)pyrene (ind.)	2.06E-03	1.34E-01	5.35E+01
Soil	benzotrichloride (ind.)	1.32E-01	8.57E+00	3.43E+03
Soil	benzylchloride (ind.)	4.16E-05	2.70E-03	1.08E+00

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Soil	beta-chlorocyclohexan (agr.)	7.36E-03	4.78E-01	1.91E+02
Soil	bromodichloromethane (ind.)	7.82E-05	5.08E-03	2.03E+00
Soil	Cadmium (ind.)	3.98E-03	2.58E-01	1.03E+02
Soil	Chromium (ind.)	2.71E-01	1.76E+01	7.04E+03
Soil	di(2-ethylhexyl)phthalate(ind)	3.18E-07	2.06E-05	8.26E-03
Soil	dibenz(a)anthracene (ind.)	2.44E+01	1.58E+03	6.34E+05
Soil	dichloromethane (ind.)	5.99E-06	3.89E-04	1.56E-01
Soil	Dichlorvos (agr.)	2.25E-05	1.46E-03	5.84E-01
Soil	2,3,7,8-TCDD Dioxin (ind.)	7.06	4.58E+02	1.83E+05
Soil	epichlorohydrin (ind.)	1.30E-06	8.44E-05	3.38E-02
Soil	ethyleneoxide (ind.)	2.38E-03	1.55E-01	6.18E+01
Soil	formaldehyde (ind.)	1.83E-06	1.19E-04	4.75E-02
Soil	gamma-HCH (Lindane) (agr.)	8.64E-03	5.61E-01	2.24E+02
Soil	hexachlorobenzene (ind.)	1.47E-01	9.55E+00	3.82E+03
Soil	Nickel (ind.)	3.94E-03	2.56E-01	1.02E+02
Soil	Nickel-refinery-dust (ind.)	6.37E-03	4.14E-01	1.65E+02
Soil	Nickel-subsulfide (ind.)	1.27E-02	8.25E-01	3.30E+02
Soil	PCBs (ind.)	2.04E-02	1.32E+00	5.30E+02
Soil	pentachlorophenol (ind.)	1.26E-05	8.18E-04	3.27E-01
Soil	propyleneoxide (ind.)	1.40E-04	9.09E-03	3.64E+00
Soil	styrene (ind.)	2.09E-08	1.36E-06	5.43E-04
Soil	perchloroethylene (ind.)	6.00E-06	3.90E-04	1.56E-01
Soil	carbontetrachloride (ind.)	3.99E-02	2.59E+00	1.04E+03
Soil	chloroform (ind.)	4.12E-06	2.68E-04	1.07E-01
Soil	vinylchloride (ind.)	7.67E-07	4.98E-05	1.99E-02

1.1.2 Respiratory effects on humans caused by organic substances (H,A)

This impact category replaces more or less the summer smog category. Fate analysis is based on empirical data. All damage factors are expressed per kg emitted substance. The unit of damage is DALYs.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	1,1,1-trichloroethane	1.96E-08	1.27E-06	5.09E-04
Air	1,2,3-trimethyl benzene	2.72E-06	1.77E-04	7.06E-02
Air	1,2,4-trimethyl benzene	2.72E-06	1.77E-04	7.06E-02
Air	1,3,5-trimethyl benzene	2.98E-06	1.94E-04	7.74E-02
Air	1,3-butadiene	1.87E-06	1.21E-04	4.86E-02
Air	1-butene	2.30E-06	1.49E-04	5.97E-02
Air	1-butoxy propanol	9.36E-07	6.08E-05	2.43E-02
Air	1-hexene	1.87E-06	1.21E-04	4.86E-02
Air	1-methoxy 2-propanol	7.91E-07	5.14E-05	2.05E-02
Air	1-pentene	2.13E-06	1.38E-04	5.53E-02
Air	2,2-dimethyl butane	5.19E-07	3.37E-05	1.35E-02
Air	2,3-dimethyl butane	1.19E-06	7.73E-05	3.09E-02
Air	2-butoxy ethanol	9.36E-07	6.08E-05	2.43E-02
Air	2-ethoxy ethanol	8.34E-07	5.42E-05	2.17E-02
Air	2-hexanone	1.19E-06	7.73E-05	3.09E-02
Air	2-methoxy ethanol	6.47E-07	4.20E-05	1.68E-02
Air	2-methyl 1-butanol	8.51E-07	5.53E-05	2.21E-02
Air	2-methyl 1-butene	1.70E-06	1.10E-04	4.42E-02
Air	2-methyl 2-butanol	3.06E-07	1.99E-05	7.95E-03
Air	2-methyl 2-butene	1.79E-06	1.16E-04	4.65E-02
Air	2-methyl hexane	8.51E-07	5.53E-05	2.21E-02
Air	2-methyl pentane	9.36E-07	6.08E-05	2.43E-02
Air	2-pentanone	1.19E-06	7.73E-05	3.09E-02
Air	3,5-diethyl toluene	2.81E-06	1.82E-04	7.30E-02
Air	3,5-dimethyl ethyl benzene	2.81E-06	1.82E-04	7.30E-02
Air	3-hexanone	1.28E-06	8.31E-05	3.32E-02
Air	3-methyl 1-butanol	8.51E-07	5.53E-05	2.21E-02
Air	3-methyl 1-butene	1.45E-06	9.42E-05	3.77E-02
Air	3-methyl 2-butanol	7.91E-07	5.14E-05	2.05E-02
Air	3-methyl hexane	7.83E-07	5.08E-05	2.03E-02
Air	3-methyl pentane	1.02E-06	6.62E-05	2.65E-02
Air	3-pentanol	9.36E-07	6.08E-05	2.43E-02
Air	3-pentanone	8.51E-07	5.53E-05	2.21E-02
Air	acetaldehyde	1.36E-06	8.83E-05	3.53E-02
Air	acetic acid	2.13E-07	1.38E-05	5.53E-03
Air	acetone	2.04E-07	1.32E-05	5.30E-03
Air	propionaldehyde	1.70E-06	1.10E-04	4.42E-02

Air	alcohols	7.60E-07	4.94E-05	1.97E-02
Air	aldehydes	1.40E-06	9.09E-05	3.64E-02
Air	alkanes	7.50E-07	4.87E-05	1.95E-02
Air	alkenes	2.10E-06	1.36E-04	5.45E-02
Air	benzene	4.68E-07	3.04E-05	1.22E-02
Air	butane	7.57E-07	4.92E-05	1.97E-02
Air	butanol	1.36E-06	8.83E-05	3.53E-02
Air	butene	2.47E-06	1.60E-04	6.42E-02
Air	cis 1,2-dichloroethene	9.36E-07	6.08E-05	2.43E-02
Air	cis 2-butene	2.47E-06	1.60E-04	6.42E-02
Air	cis 2-hexene	2.30E-06	1.49E-04	5.97E-02
Air	cis 2-pentene	2.38E-06	1.55E-04	6.18E-02
Air	CxHy aromatic	2.10E-06	1.36E-04	5.45E-02
Air	CxHy chloro	3.50E-07	2.27E-05	9.09E-03
Air	CxHy halogenated	3.50E-07	2.27E-05	9.09E-03
Air	cyclohexane	6.21E-07	4.03E-05	1.61E-02
Air	cyclohexanol	9.36E-07	6.08E-05	2.43E-02
Air	cyclohexanone	6.47E-07	4.20E-05	1.68E-02
Air	decane	8.26E-07	5.36E-05	2.15E-02
Air	di-i-propyl ether	1.02E-06	6.62E-05	2.65E-02
Air	diacetone alcohol	5.62E-07	3.65E-05	1.46E-02
Air	dichloromethane	1.45E-07	9.42E-06	3.77E-03
Air	diethyl ether	1.02E-06	6.62E-05	2.65E-02
Air	dimethyl ether	3.74E-07	2.43E-05	9.71E-03
Air	dodecane	7.66E-07	4.97E-05	1.99E-02
Air	esters	3.70E-07	2.40E-05	9.61E-03
Air	ethane	2.64E-07	1.71E-05	6.86E-03
Air	ethane diol	8.26E-07	5.36E-05	2.15E-02
Air	ethanol	8.34E-07	5.42E-05	2.17E-02
Air	ethene	2.13E-06	1.38E-04	5.53E-02
Air	ethers	7.40E-07	4.81E-05	1.92E-02
Air	ethyl t-butyl ether	4.60E-07	2.99E-05	1.19E-02
Air	ethylacetate	4.60E-07	2.99E-05	1.19E-02
Air	ethylbenzene	1.53E-06	9.94E-05	3.97E-02
Air	acetylene	1.87E-07	1.21E-05	4.86E-03
Air	formaldehyde	1.11E-06	7.21E-05	2.88E-02
Air	formic acid	6.89E-08	4.47E-06	1.79E-03
Air	heptane	1.11E-06	7.21E-05	2.88E-02
Air	hexane	1.02E-06	6.62E-05	2.65E-02
Air	i-butane	6.64E-07	4.31E-05	1.72E-02
Air	i-butanol	8.09E-07	5.25E-05	2.10E-02
Air	i-butyraldehyde	1.11E-06	7.21E-05	2.88E-02
Air	i-pentane	8.51E-07	5.53E-05	2.21E-02
Air	i-propanol	2.98E-07	1.94E-05	7.74E-03
Air	i-propyl acetate	4.60E-07	2.99E-05	1.19E-02
Air	i-propyl benzene	1.11E-06	7.21E-05	2.88E-02
Air	isoprene	2.38E-06	1.55E-04	6.18E-02
Air	ketones	8.70E-07	5.65E-05	2.26E-02
Air	m-ethyl toluene	2.21E-06	1.44E-04	5.74E-02
Air	m-xylene	2.38E-06	1.55E-04	6.18E-02
Air	methane	1.28E-08	8.31E-07	3.32E-04
Air	methanol	2.81E-07	1.82E-05	7.30E-03
Air	methyl acetate	1.02E-07	6.62E-06	2.65E-03
Air	methyl chloride	1.11E-08	7.21E-07	2.88E-04
Air	methyl ethyl ketone	8.09E-07	5.25E-05	2.10E-02
Air	methyl formate	7.15E-08	4.64E-06	1.86E-03
Air	methyl i-butyl ketone	1.02E-06	6.62E-05	2.65E-02
Air	methyl i-propyl ketone	7.83E-07	5.08E-05	2.03E-02
Air	methyl propene	1.36E-06	8.83E-05	3.53E-02
Air	methyl t-butyl ether	3.32E-07	2.16E-05	8.62E-03
Air	methyl t-butyl ketone	6.98E-07	4.53E-05	1.81E-02
Air	n-butanol	1.36E-06	8.83E-05	3.53E-02
Air	n-butyl acetate	5.19E-07	3.37E-05	1.35E-02
Air	n-butyraldehyde	1.70E-06	1.10E-04	4.42E-02
Air	n-propanol	1.19E-06	7.73E-05	3.09E-02
Air	n-propyl acetate	6.21E-07	4.03E-05	1.61E-02
Air	n-propyl benzene	1.36E-06	8.83E-05	3.53E-02
Air	neopentane	3.74E-07	2.43E-05	9.71E-03
Air	NMVO	1.28E-06	8.31E-05	3.32E-02
Air	nonane	8.51E-07	5.53E-05	2.21E-02
Air	o-ethyl toluene	1.96E-06	1.27E-04	5.09E-02
Air	o-xylene	2.30E-06	1.49E-04	5.97E-02
Air	octane	9.36E-07	6.08E-05	2.43E-02
Air	p-ethyl toluene	1.96E-06	1.27E-04	5.09E-02

Air	p-xylene	2.21E-06	1.44E-04	5.74E-02
Air	pentanal	1.62E-06	1.05E-04	4.21E-02
Air	pentane	8.51E-07	5.53E-05	2.21E-02
Air	propane	3.83E-07	2.49E-05	9.95E-03
Air	propane diol	1.02E-06	6.62E-05	2.65E-02
Air	propene	2.38E-06	1.55E-04	6.18E-02
Air	propanoic acide	3.23E-07	2.10E-05	8.39E-03
Air	s-butanol	8.51E-07	5.53E-05	2.21E-02
Air	s-butyl acetate	5.79E-07	3.76E-05	1.50E-02
Air	t-butanol	2.64E-07	1.71E-05	6.86E-03
Air	t-butyl acetate	1.36E-07	8.83E-06	3.53E-03
Air	perchloroethylene	6.21E-08	4.03E-06	1.61E-03
Air	toluene	1.36E-06	8.83E-05	3.53E-02
Air	trans 1,2-dichloroethene	8.43E-07	5.47E-05	2.19E-02
Air	trans 2-butene	2.47E-06	1.60E-04	6.42E-02
Air	trans 2-hexene	2.30E-06	1.49E-04	5.97E-02
Air	trans 2-pentene	2.38E-06	1.55E-04	6.18E-02
Air	trichloroethylene	6.98E-07	4.53E-05	1.81E-02
Air	chloroform	4.94E-08	3.21E-06	1.28E-03
Air	undecane	8.26E-07	5.36E-05	2.15E-02
Air	VOC	6.46E-07	4.19E-05	1.68E-02
Air	xylene	2.21E-06	1.44E-04	5.74E-02

1.1.3 Respiratory effects on humans caused by inorganic substances (H,A)

This impact category replaces more or less the winter smog category. Fate analysis is based on empirical data.

All damage factors are expressed per kg emission. The unit of damage is DALYs.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	ammonia	8.50E-05	5.52E-03	2.21E+00
Air	dust (PM10)	3.75E-04	2.44E-02	9.74E+00
Air	dust (PM2.5)	7.00E-04	4.55E-02	1.82E+01
Air	TSP	1.10E-04	7.14E-03	2.86E+00
Air	NO	1.37E-04	8.90E-03	3.56E+00
Air	NO2	8.87E-05	5.76E-03	2.30E+00
Air	NOx	8.87E-05	5.76E-03	2.30E+00
Air	NOx (as NO2)	8.87E-05	5.76E-03	2.30E+00
Air	SO2	5.46E-05	3.55E-03	1.42E+00
Air	SO3	4.37E-05	2.84E-03	1.14E+00
Air	SOx	5.46E-05	3.55E-03	1.42E+00
Air	SOx (as SO2)	5.46E-05	3.55E-03	1.42E+00

1.1.4 Damages to human health caused by climate change (H,A)

Damage calculation was performed over a time scale of 200 years. The IPCC equivalence factors have been modified. As damage is not linear dependent on the atmospheric lifetime, a separate damage calculation is made for CO₂, CH₄ en CH₄:

- Gasses with an atmospheric lifetime below 20 years are assumed to behave like methane
- Gasses with an atmospheric lifetime between 20 and 100 years behave like CO₂
- Gasses with an atmospheric lifetime oh more than 100 years are assumed to behave like N₂O

This means that the IPCC equivalency factor table is split in three groups.

All damage factors are expressed per kg substance. The unit of damage is DALYs.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	methyl chloroform	-4.3E-05	-2.79E-03	-1.12E+00
Air	perfluorethane	2.00E-03	1.30E-01	5.19E+01
Air	trifluoriodomethane	2.10E-07	1.36E-05	5.45E-03

Air	perfluormethane	1.40E-03	9.09E-02	3.64E+01
Air	CFC-11	2.20E-04	1.43E-02	5.71E+00
Air	CFC-113	6.30E-04	4.09E-02	1.64E+01
Air	CFC-12	1.40E-03	9.09E-02	3.64E+01
Air	carbon dioxide	2.10E-07	1.36E-05	5.45E-03
Air	methylene chloride	1.90E-06	1.23E-04	4.94E-02
Air	HALON-1301	-7.10E-03	-4.61E-01	-1.84E+02
Air	HCFC-123	6.60E-06	4.29E-04	1.71E-01
Air	HCFC-124	8.50E-05	5.52E-03	2.21E+00
Air	HCFC-141b	5.20E-05	3.38E-03	1.35E+00
Air	HCFC-142b	3.40E-04	2.21E-02	8.83E+00
Air	HCFC-22	2.80E-04	1.82E-02	7.27E+00
Air	HFC-125	5.70E-04	3.70E-02	1.48E+01
Air	HFC-134	2.10E-04	1.36E-02	5.45E+00
Air	HFC-134a	2.70E-04	1.75E-02	7.01E+00
Air	HFC-143	6.30E-05	4.09E-03	1.64E+00
Air	HFC-143a	7.80E-04	5.06E-02	2.03E+01
Air	HFC-152a	2.90E-05	1.88E-03	7.53E-01
Air	HFC-227ea	5.90E-04	3.83E-02	1.53E+01
Air	HFC-23	2.60E-03	1.69E-01	6.75E+01
Air	HFC-236fa	1.40E-03	9.09E-02	3.64E+01
Air	HFC-245ca	1.20E-04	7.79E-03	3.12E+00
Air	HFC-32	1.40E-04	9.09E-03	3.64E+00
Air	HFC-41	3.10E-05	2.01E-03	8.05E-01
Air	HFC-4310mee	2.70E-04	1.75E-02	7.01E+00
Air	methane	4.40E-06	2.86E-04	1.14E-01
Air	nitrous oxide	6.90E-05	4.48E-03	1.79E+00
Air	perfluorbutane	1.50E-03	9.74E-02	3.90E+01
Air	perfluorocyclobutane	1.90E-03	1.23E-01	4.94E+01
Air	perfluorhexane	1.60E-03	1.04E-01	4.16E+01
Air	perfluoropentane	1.70E-03	1.10E-01	4.42E+01
Air	perfluoropropane	1.50E-03	9.74E-02	3.90E+01
Air	sulphur hexafluoride	5.30E-03	3.44E-01	1.38E+02
Air	carbontetrachloride	-2.60E-04	-1.69E-02	-6.75E+00
Air	chloroform	8.30E-07	5.39E-05	2.16E-02

1.1.5 Human health effects caused by ionising radiation (H,A)

Fate-, and exposure models are based on studies for the French nuclear industry. All damage factors are based on a release of 1 Becquerel (Bq). The unit of damage is DALYs.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	C-14	2.10E-10	1.36E-08	5.45E-06
Air	Co-58	4.30E-13	2.79E-11	1.12E-08
Air	Co-60	1.60E-11	1.04E-09	4.16E-07
Air	Cs-134	1.20E-11	7.79E-10	3.12E-07
Air	Cs-137	1.30E-11	8.44E-10	3.38E-07
Air	H-3	1.40E-14	9.09E-13	3.64E-10
Air	I-129	9.40E-10	6.10E-08	2.44E-05
Air	I-131	1.60E-13	1.04E-11	4.16E-09
Air	I-133	9.40E-15	6.10E-13	2.44E-10
Air	Kr-85	1.40E-16	9.09E-15	3.64E-12
Air	Pb-210	1.50E-12	9.74E-11	3.90E-08
Air	Po-210	1.50E-12	9.74E-11	3.90E-08
Air	Pu alpha	8.30E-11	5.39E-09	2.16E-06
Air	Pu-238	6.70E-11	4.35E-09	1.74E-06
Air	Ra-226	9.10E-13	5.91E-11	2.36E-08
Air	Rn-222	2.40E-14	1.56E-12	6.23E-10
Air	Th-230	4.50E-11	2.92E-09	1.17E-06
Air	U-234	9.70E-11	6.30E-09	2.52E-06
Air	U-235	2.10E-11	1.36E-09	5.45E-07
Air	U-238	8.20E-12	5.32E-10	2.13E-07
Air	Xe-133	1.40E-16	9.09E-15	3.64E-12
Water	Ag-110m	5.10E-13	3.31E-11	1.32E-08
Water	Co-58	4.10E-14	2.66E-12	1.06E-09
Water	Co-60	4.40E-11	2.86E-09	1.14E-06
Water	Cs-134	1.40E-10	9.09E-09	3.64E-06
Water	Cs-137	1.70E-10	1.10E-08	4.42E-06
Water	H-3	4.50E-16	2.92E-14	1.17E-11

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Water	I-131	5.00E-13	3.25E-11	1.30E-08
Water	Mn-54	3.10E-13	2.01E-11	8.05E-09
Water	Ra-226	1.30E-13	8.44E-12	3.38E-09
Water	Sb-124	8.20E-13	5.32E-11	2.13E-08
Water	U-234	2.40E-12	1.56E-10	6.23E-08
Water	U-235	2.30E-12	1.49E-10	5.97E-08
Water	U-238	2.30E-12	1.49E-10	5.97E-08

1.1.6 Human health effects caused by ozone layer depletion (H,A)

All damage factors are expressed per kg release. The unit of damage is DALYs.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	1,1,1-trichloroethane	1.26E-04	8.18E-03	3.27E+00
Air	CFC-11	1.05E-03	6.82E-02	2.73E+01
Air	CFC-113	9.48E-04	6.16E-02	2.46E+01
Air	CFC-114	8.95E-04	5.81E-02	2.32E+01
Air	CFC-115	4.21E-04	2.73E-02	1.09E+01
Air	CFC-12	8.63E-04	5.60E-02	2.24E+01
Air	HALON-1201	1.47E-03	9.55E-02	3.82E+01
Air	HALON-1202	1.32E-03	8.57E-02	3.43E+01
Air	HALON-1211	5.37E-03	3.49E-01	1.39E+02
Air	HALON-1301	1.26E-02	8.18E-01	3.27E+02
Air	HALON-2311	1.47E-04	9.55E-03	3.82E+00
Air	HALON-2401	2.63E-04	1.71E-02	6.83E+00
Air	HALON-2402	7.37E-03	4.79E-01	1.91E+02
Air	HCFC-123	1.47E-05	9.55E-04	3.82E-01
Air	HCFC-124	3.16E-05	2.05E-03	8.21E-01
Air	HCFC-141b	1.05E-04	6.82E-03	2.73E+00
Air	HCFC-142b	5.26E-05	3.42E-03	1.37E+00
Air	HCFC-22	4.21E-05	2.73E-03	1.09E+00
Air	HCFC-225ca	2.11E-05	1.37E-03	5.48E-01
Air	HCFC-225cb	2.11E-05	1.37E-03	5.48E-01
Air	methyl bromide	6.74E-04	4.38E-02	1.75E+01
Air	methyl chloride	2.11E-05	1.37E-03	5.48E-01
Air	carbontetrachloride	1.26E-03	8.18E-02	3.27E+01

1.2 Damage category Ecosystem Quality (H,A)

The Ecosystem Quality damages are specified as PDF*m²*yr. PDF is short for Potentially Disappeared Fraction of Species. A damage of one means all species disappear from one m² during one year, or 10% of all species disappear from 10 m² during one year, or 10% of all species disappear from 1 m² during 10 years. Within the damage category Ecosystem Quality, special care is needed to avoid double counting when land-use is modelled. See the remarks under these damage categories.

1.2.1 Damage to Ecosystem Quality caused by ecotoxic emissions (H,A)

Fate analysis was done in EUSES. Pesticides that evaporate during application must be counted as air emissions. Pesticides that are accidentally sprayed in surface waters must be counted as water emissions. The remainder must be counted as soil emissions. The damage from pesticides in the agricultural soil as such (root zone) was deliberately excluded to avoid double counting with land-use. This means the damage factors in this list are based on secondary (leaching) emissions from the soil into surface and ground water and evaporation.

All damage factors are expressed per kg release. The unit of damage is PDF*m²*yr.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	1,2,3-trichlorobenzene	3.51E-02	6.84E-06	2.74E-03
Air	1,2,4-trichlorobenzene	2.54E-02	4.95E-06	1.98E-03
Air	1,3,5-trichlorobenzene	1.29E-01	2.51E-05	1.01E-02
Air	2,4-D	1.46E+00	2.85E-04	1.14E-01
Air	Arsenic	5.92E+02	1.15E-01	4.62E+01
Air	Atrazine	2.09E+02	4.07E-02	1.63E+01
Air	Azinphos-methyl	1.10E+04	2.14E+00	8.58E+02
Air	Bentazon	7.33E+00	1.43E-03	5.72E-01
Air	benzene	2.75E-03	5.36E-07	2.14E-04
Air	benzo(a)pyrene	1.42E+02	2.77E-02	1.11E+01
Air	Carbendazim	2.40E+03	4.68E-01	1.87E+02
Air	Cadmium	9.65E+03	1.88E+00	7.52E+02
Air	Chromium	4.13E+03	8.05E-01	3.22E+02
Air	Copper	1.46E+03	2.85E-01	1.14E+02
Air	di(2-ethylhexyl)phthalate	1.94E+03	3.78E-07	1.51E-04
Air	dibutylphthalate	1.13E-01	2.20E-05	8.81E-03
Air	Dichlorvos	1.61E+00	3.14E-04	1.26E-01
Air	2,3,7,8-TCDD Dioxin	1.32E+05	2.57E+01	1.03E+04
Air	Diquat-dibromide	2.39E+03	4.66E-01	1.86E+02
Air	Diuron	4.43E+03	8.64E-01	3.45E+02
Air	DNOC	8.19E+00	1.60E-03	6.39E-01
Air	fentin acetate	6.77E+02	1.32E-01	5.28E+01
Air	fluoranthene	4.37E-02	8.52E-06	3.41E-03
Air	gamma-HCH (Lindane)	2.16E+00	4.21E-04	1.68E-01
Air	Hexachlorobenzene	3.88E+01	7.56E-03	3.03E+00
Air	Mercury	8.29E+02	1.62E-01	6.46E+01
Air	Malathion	1.17E+02	2.28E-02	9.12E+00
Air	Maneb	3.84E+01	7.49E-03	2.99E+00
Air	Mecoprop	7.79E-02	1.52E-05	6.07E-03
Air	Metabenzthiazuron	3.07E+02	5.98E-02	2.39E+01
Air	metals	2.60E+02	5.07E-02	2.03E+01
Air	Metamitron	3.78E+01	7.37E-03	2.95E+00
Air	Metribuzin	4.92E+02	9.59E-02	3.84E+01
Air	Mevinphos	2.13E+03	4.15E-01	1.66E+02
Air	Monolinuron	1.06E+02	2.07E-02	8.27E+00
Air	Nickel	7.10E+03	1.38E+00	5.54E+02
Air	PAH's	7.80E-04	1.52E-07	6.08E-05
Air	Parathion	6.05E+01	1.18E-02	4.72E+00
Air	Lead	2.54E+03	4.95E-01	1.98E+02
Air	Polychlorobiphenyls	8.07E+01	1.57E-02	6.29E+00
Air	pentachlorophenol	1.33E+01	2.59E-03	1.04E+00
Air	Simazine	1.44E+03	2.81E-01	1.12E+02
Air	Thiram	2.26E+02	4.41E-02	1.76E+01
Air	toluene	2.40E-04	4.68E-08	1.87E-05
Air	Trifluralin	1.09E+00	2.12E-04	8.50E-02
Air	Zinc	2.89E+03	5.63E-01	2.25E+02
Water	1,2,3-trichlorobenzene	1.56E-01	3.04E-05	1.22E-02
Water	1,2,4-trichlorobenzene	1.39E-01	2.71E-05	1.08E-02
Water	1,3,5-trichlorobenzene	2.73E-01	5.32E-05	2.13E-02
Water	2,4-D	7.56E-02	1.47E-05	5.89E-03
Water	Arsenic	1.14E+01	2.22E-03	8.89E-01
Water	Atrazine	5.06E+01	9.86E-03	3.95E+00
Water	Azinphos-methyl	8.87E+02	1.73E-01	6.92E+01
Water	Bentazon	5.81E-02	1.13E-05	4.53E-03
Water	benzene	4.80E-02	9.36E-06	3.74E-03
Water	benzo(a)pyrene	3.68E+01	7.17E-03	2.87E+00
Water	Carbendazim	1.63E+02	3.18E-02	1.27E+01
Water	Cadmium	4.80E+02	9.36E-02	3.74E+01
Water	Chromium	6.87E+01	1.34E-02	5.36E+00
Water	Copper	1.47E+02	2.87E-02	1.15E+01
Water	di(2-ethylhexyl)phthalate	6.37E-01	1.24E-04	4.97E-02
Water	dibutylphthalate	1.62E+00	3.16E-04	1.26E-01
Water	Dichlorvos	1.81E-01	3.53E-05	1.41E-02
Water	dioxins (TEQ)	1.87E+05	3.65E+01	1.46E+04
Water	Diquat-dibromide	1.18E+02	2.30E-02	9.20E+00
Water	Diuron	2.31E+02	4.50E-02	1.80E+01
Water	DNOC	6.73E-01	1.31E-04	5.25E-02
Water	fentin acetate	7.85E+02	1.53E-01	6.12E+01
Water	fluoranthene	3.96E+00	7.72E-04	3.09E-01
Water	gamma-HCH (Lindane)	1.04E+01	2.03E-03	8.11E-01
Water	hexachlorobenzene	4.55E+01	8.87E-03	3.55E+00

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Water	Mercury	1.97E+02	3.84E-02	1.54E+01
Water	Malathion	1.64E+02	3.20E-02	1.28E+01
Water	Maneb	6.23E-01	1.21E-04	4.86E-02
Water	Mecoprop	1.35E-02	2.63E-06	1.05E-03
Water	Metabenzthiazuron	1.43E+01	2.79E-03	1.12E+00
Water	Metamitron	3.77E-01	7.35E-05	2.94E-02
Water	Metribuzin	3.18E+00	6.20E-04	2.48E-01
Water	Mevinphos	6.73E+01	1.31E-02	5.25E+00
Water	Monolinuron	1.04E+01	2.03E-03	8.11E-01
Water	Nickel	1.43E+02	2.79E-02	1.12E+01
Water	PAH's	2.10E-03	4.09E-07	1.64E-04
Water	Parathion	2.48E+02	4.83E-02	1.93E+01
Water	Lead	7.39E+00	1.44E-03	5.76E-01
Water	Polychlorobiphenyls	2.58E+02	5.03E-02	2.01E+01
Water	pentachlorophenol	2.51E+01	4.89E-03	1.96E+00
Water	Simazine	6.03E+01	1.18E-02	4.70E+00
Water	Thiram	8.74E+02	1.70E-01	6.81E+01
Water	toluene	1.73E-01	3.37E-05	1.35E-02
Water	Trifluralin	7.80E+01	1.52E-02	6.08E+00
Water	Zinc	1.63E+01	3.18E-03	1.27E+00
Soil	1,2,3-trichlorobenzene (ind.)	2.41E+00	4.70E-04	1.88E-01
Soil	1,2,4-trichlorobenzene (ind.)	2.26E+00	4.41E-04	1.76E-01
Soil	1,3,5-trichlorobenzene (ind.)	1.19E+00	2.32E-04	9.28E-02
Soil	2,4-D (agr.)	1.27E-04	2.48E-08	9.90E-06
Soil	Arsenic (ind.)	6.10E+02	1.19E-01	4.76E+01
Soil	Atrazine (agr.)	1.49E-01	2.90E-05	1.16E-02
Soil	Azinphos-methyl (agr.)	3.55E-01	6.92E-05	2.77E-02
Soil	Bentazon (agr.)	1.66E-02	3.24E-06	1.29E-03
Soil	benzene (ind.)	4.97E-01	9.69E-05	3.88E-02
Soil	benzo(a)pyrene (ind.)	7.25E+03	1.41E+00	5.65E+02
Soil	Carbendazim (agr.)	2.34E+00	4.56E-04	1.82E-01
Soil	Cadmium (agr.)	3.01E+01	5.87E-03	2.35E+00
Soil	Cadmium (ind.)	9.94E+03	1.94E+00	7.75E+02
Soil	Chromium (ind.)	4.24E+03	8.27E-01	3.31E+02
Soil	Copper (ind.)	1.50E+03	2.92E-01	1.17E+02
Soil	di(2-ethylhexyl)phthalate(ind.)	2.67E-02	5.20E-06	2.08E-03
Soil	dibutylphthalate (ind.)	1.14E+00	2.22E-04	8.89E-02
Soil	Dichlorvos (agr.)	7.52E-04	1.47E-07	5.86E-05
Soil	2,3,7,8-TCDD Dioxin (ind.)	2.09E+05	4.07E+01	1.63E+04
Soil	Diquat dibromide (agr.)	6.84E-02	1.33E-05	5.33E-03
Soil	Diuron (agr.)	4.07E-02	7.93E-06	3.17E-03
Soil	DNOC (agr.)	6.17E-03	1.20E-06	4.81E-04
Soil	fentin acetate (agr.)	3.84E-01	7.49E-05	2.99E-02
Soil	fluoranthene (ind.)	8.00E+00	1.56E-03	6.24E-01
Soil	gamma-HCH (Lindane) (agr.)	1.38E+00	2.69E-04	1.08E-01
Soil	hexachlorobenzene (ind.)	9.96E+01	1.94E-02	7.77E+00
Soil	Mercury (ind.)	1.68E+03	3.27E-01	1.31E+02
Soil	Malathion (agr.)	2.79E-02	5.44E-06	2.18E-03
Soil	Maneb (agr.)	2.61E-01	5.09E-05	2.04E-02
Soil	Mecoprop (agr.)	2.79E-06	5.44E-10	2.18E-07
Soil	Metabenzthiazuron (agr.)	3.15E-01	6.14E-05	2.46E-02
Soil	Metamitron (agr.)	2.03E-04	3.96E-08	1.58E-05
Soil	Metribuzin (agr.)	4.91E-02	9.57E-06	3.83E-03
Soil	Mevinphos (agr.)	2.09E-01	4.07E-05	1.63E-02
Soil	Monolinuron (agr.)	4.38E-01	8.54E-05	3.42E-02
Soil	Nickel (ind.)	7.32E+03	1.43E+00	5.71E+02
Soil	Parathion (agr.)	3.24E-02	6.32E-06	2.53E-03
Soil	Lead (ind.)	1.29E+01	2.51E-03	1.01E+00
Soil	PCBs (ind.)	8.35E+02	1.63E-01	6.51E+01
Soil	pentachlorophenol (ind.)	2.51E+01	4.89E-03	1.96E+00
Soil	Simazine (agr.)	3.87E-01	7.54E-05	3.02E-02
Soil	Thiram (agr.)	9.96E-01	1.94E-04	7.77E-02
Soil	toluene (ind.)	6.79E-02	1.32E-05	5.29E-03
Soil	Trifluralin (agr.)	2.07E-02	4.04E-06	1.61E-03
Soil	Zinc (ind.)	2.98E+03	5.81E-01	2.32E+02

1.2.2 Damage to Ecosystem Quality caused by the combined effect of acidification and eutrophication (H,A)

Unfortunately no damage factors for emissions to water and soil could yet be calculated. We suggest to use the damage factors for air as a temporary, but crude solution.

The damage caused by fertilisers that are deliberately applied on agricultural soil is already included in the land-use damage factors, and should not be treated as an emission leading to eutrophication. The fertilisers that evaporate, or that are accidentally sprayed in surface waters should be counted as an emission.

All damage factors are based on kg emissions to air. The unit of damage is PDF*m²*yr.

Com-part-ment	Substances	Damage factor	Normalised damage factor	Weighted damage factor
Air	ammonia	15,57	3,04E-03	1,21E+00
Air	NO	8,789	1,71E-03	6,85E-01
Air	NO2	5,713	1,11E-03	4,45E-01
Air	NOx	5,713	1,11E-03	4,45E-01
Air	NOx (as NO2)	5,713	1,11E-03	4,45E-01
Air	SO2	1,041	2,03E-04	8,12E-02
Air	SO3	0,8323	1,62E-04	6,49E-02
Air	SOx	1,041	2,03E-04	8,12E-02
Air	SOx (as SO2)	1,041	2,03E-04	8,12E-02

1.2.3 Damage to Ecosystem Quality caused by land occupation and land conversion (H,A)

It is important to separate two cases:

- Land occupation
- Land conversion

The damage factors for occupation are per area [m²] times the duration of the occupation [yr]. The effect of restoration of the area type to its natural condition is not included here, but in the land conversion damage factors. Occupation is seen as a damage, because the area is prevented from restoring to its natural area. Typical examples of land occupation are:

Building new houses in an existing urban area, using a factory in an industrial area, agricultural production in an existing agricultural area. In most cases land is used that has already been converted long ago. In such cases conversion should not be considered.

The damage factors for conversions are per area [m²]. Conversion factors should only be used if it is clear that a process results in the conversion of one area type into another. Examples are: mining operations in natural areas, expanding agricultural areas at the expense of natural areas, and dumping waste. The difference with the factors for occupation is the inclusion of a restoration time that has been set to 30 years as default. Other restoration times can be easily calculated by dividing the damage factors by 30 and multiplying them with the intended restoration time.

Conversions between agricultural and urban area types can also be modelled by subtracting the damage factors, but, as the damage factors can have considerable uncertainties, the result is unreliable. We suggest to use conversion data only for cases where natural areas are converted into non-natural area types.

1.2.3.1 COMPATIBILITY WITH ESU DATABASE

The ESU database, produced at the ETH Zurich, is one of the few large databases that has consistently included land-use data. Unfortunately no distinction is made between conversion and occupation, the two are always combined. This means a restoration time is always included, and this restoration time cannot be separated in a elegant way. In order to be able to use this large database damage factors: land-use II-III, land use II-IV,

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land-use III-IV and land-use IV-IV have been estimated using the following (rather crude) assumptions:

- ESU land-use type II can be interpreted as near to natural area
- ESU land-use type III can be interpreted as green urban or rail areas. These are the not very intensively used areas
- ESU land-use type IV can be interpreted as continuous urban land
- ESU assumes a 5 year restoration time between type IV and III. In many cases an occupation time for industrial activities of 25 or 30 years is used. As a result the restoration time results in an overestimation of 20% for land-use II-IV. In the figure presented here the damage factor is thus lowered by 20%.
- After the conversion from Land-use II-IV the ESU database uses the factors II-III for the restoration time between type II and III. As we do not want to include these, in general they should be omitted. Unfortunately for processes like the production of hydropower this class is used in a different way and should thus be included

Using the ESU database is thus not very straightforward, but with the factors presented here a reasonable first order approximation can be obtained, except for instance for processes that involve agricultural production and hydropower.

1.2.3.2 DOUBLE COUNTING

The damage factors are based on empirical observations of the number of plant species per area type. In such observations all effects of the area type are included. This means that also the effects of emissions are included. To avoid double counting these emissions, please observe the guidelines for pesticides and eutrophication.

The unit of damage of land occupation is PDF*m²*yr.

Land-occupation	Damage factor	Normalised damage factor	Weighted damage factor
land use II-III	0.51	9.94E-05	3.98E-02
land use II-IV	0.96	1.87E-04	7.49E-02
land use III-IV	0.96	1.87E-04	7.49E-02
land use IV-IV	1.15	2.24E-04	8.97E-02
Occup. as Contin. urban land	1.15	2.24E-04	8.97E-02
Occup. as Convent. arable land	1.15	2.24E-04	8.97E-02
Occup. as Discont. urban land	0.96	1.87E-04	7.49E-02
Occup. as Forest land	0.11	2.14E-05	8.58E-03
Occup. as Green urban land	0.84	1.64E-04	6.55E-02
Occup. as Industrial area	0.84	1.64E-04	6.55E-02
Occup. as Intens. meadow land	1.13	2.20E-04	8.81E-02
Occup. as Organic arable land	1.09	2.12E-04	8.50E-02
Occup. as organic meadow land	1.02	1.99E-04	7.95E-02
Occup. as rail/ road area	0.84	1.64E-04	6.55E-02
Occup. as Integrated arable land	1.15	2.24E-04	8.97E-02
Occup. as less intens. meadow land	1.02	1.99E-04	7.95E-02

The unit of damage of land conversion is PDF*m².

Land conversion	Damage factor	Normalised damage factor	Weighted damage factor
Conv. to Continuous urban land	34.53	6.73E-03	2.69E+00
Conv. to Convent. arable land	34.38	6.70E-03	2.68E+00

Conv. to Discontinuous urban	28.73	5.60E-03	2.24E+00
Conv. to Green urban	25.16	4.90E-03	1.96E+00
Conv. to Industrial area	25.16	4.90E-03	1.96E+00
Conv. to Integr. arable land	34.38	6.70E-03	2.68E+00
Conv. to Intensive meadow	34.02	6.63E-03	2.65E+00
Conv. to Less intensive meadow	30.62	5.97E-03	2.39E+00
Conv. to Organic arable land	32.73	6.38E-03	2.55E+00
Conv. to Organic meadow	30.62	5.97E-03	2.39E+00
Conv. to rail/ road area	25.16	4.90E-03	1.96E+00

1.3 Damage category Resources (H,A)

The damages to resources are specified as MJ surplus energy. A damage of 1 means that due to a certain extraction further extraction of this resource in the future will require one additional MJ of energy, due to the lower resource concentration, or other unfavourable characteristics of the remaining reserves. The point in future has been chosen as the time at which 5 times the cumulative extraction of the resource before 1990 is extracted. The factor 5 is chosen arbitrarily, but after normalisation this has no further significance.

1.3.1 Damage to Resources caused by extraction of minerals (H,A)

The damage factors are expressed per kg of extracted metal or ore:

- "in ore" refers to the metal content in the ore, so 1 kg iron (in ore) means one kg of pure iron
- "ore" refers to the ore. An average metal content is assumed to calculate these figures.

The unit of damage is MJ surplus energy per kg extracted material.

Minerals	Damage factor	Normalised damage factor	Weighted damage factor
aluminium (in ore)	2.38	2.83E-04	5.66E-02
bauxite	0.5	5.95E-05	1.19E-02
chromium (in ore)	0.9165	1.09E-04	2.18E-02
chromium (ore)	0.275	3.27E-05	6.54E-03
copper (in ore)	36.7	4.36E-03	8.73E-01
copper (ore)	0.415	4.93E-05	9.87E-03
iron (in ore)	0.051	6.06E-06	1.21E-03
iron (ore)	0.029	3.45E-06	6.90E-04
lead (in ore)	7.35	8.74E-04	1.75E-01
lead (ore)	0.368	4.38E-05	8.75E-03
manganese (in ore)	0.313	3.72E-05	7.44E-03
manganese (ore)	0.141	1.68E-05	3.35E-03
mercury (in ore)	165.5	1.97E-02	3.94E+00
molybdenum (in ore)	41	4.88E-03	9.75E-01
molybdenum (ore)	0.041	4.88E-06	9.75E-04
nickel (in ore)	23.75	2.82E-03	5.65E-01
nickel (ore)	0.356	4.23E-05	8.47E-03
tin (in ore)	600	7.13E-02	1.43E+01
tin (ore)	0.06	7.13E-06	1.43E-03
tungsten (ore)	0.927	1.10E-04	2.20E-02
zinc (in ore)	4.09	4.86E-04	9.73E-02
zinc (ore)	0.164	1.95E-05	3.90E-03

1.3.2 Damage to Resources caused by extraction of fossil fuels (H,A)

The damage factors are expressing MJ surplus energy per kg of extracted fuel, or per m³ of extracted gas, or per MJ extracted energy.

The unit of damage is MJ surplus energy.

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Fossil fuels	Unit	Damage factor	Normalised damage factor	Weighted damage factor
coal	kg	0.252	3.00E-05	5.99E-03
coal ETH	kg	0.155	1.84E-05	3.69E-03
crude gas	kg	4.2	4.99E-04	9.99E-02
crude oil	kg	5.9	7.02E-04	1.40E-01
crude oil (feedstock)	kg	5.9	7.02E-04	1.40E-01
crude oil (resource)	MJ	1.44E-01	1.71E-05	3.42E-03
crude oil ETH	kg	6.13	7.29E-04	1.46E-01
crude oil IDEMAT	kg	6.15	7.31E-04	1.46E-01
energy from coal	MJ	8.59E-03	1.02E-06	2.04E-04
energy from natural gas	MJ	1.50E-01	1.78E-05	3.57E-03
energy from oil	MJ	0.144	1.71E-05	3.42E-03
hard coal (resource)	MJ	8.59E-03	1.02E-06	2.04E-04
natural gas	kg	4.55	5.41E-04	1.08E-01
natural gas (feedstock)	m3	5.25	6.24E-04	1.25E-01
natural gas (resource)	MJ	1.50E-01	1.78E-05	3.57E-03
natural gas (vol)	m3	5.49	6.53E-04	1.31E-01
natural gas ETH	m3	5.25	6.24E-04	1.25E-01
oil	kg	6.05	7.19E-04	1.44E-01

The energy content of the fuels listed above are:

Energy Content of Fossil fuels	[MJ / unit]
natural gas ETH	35 MJ / m3
crude oil IDEMAT	42.7 MJ / kg
coal ETH	18 MJ / kg
natural gas (feedstock)	35 MJ / m3
crude oil (feedstock)	41 MJ / kg
crude oil ETH	42.6 MJ / kg
natural gas (vol)	36.6 MJ / m3
coal	29.3 MJ / kg
crude oil	41 MJ / kg
natural gas	30.3 MJ / kg
oil	42 MJ / kg
crude gas	28 MJ / kg

APPENDIX D
PUBLISHED PAPERS

The following papers are reproduced in the Appendix:

Adams, P., Hammond, G., McManus, M. C., & Mezzullo, W. 2008 "Barriers to UK Bioenergy Development: Experiences from the South West of England", *In Biomass and Energy Crops III* York: pp. 41-51.

Hammond, G., McManus, M.C., & Mezzullo, W. 2008a. "A bioenergy resource assessment for the South West of England", *Proceedings of the Institution of Civil Engineers – Energy*, vol. 161, no. 4, pp. 159-173.

*Aspects of Applied Biology 90, 2008
Biomass and Energy Crops III*

Barriers to UK bioenergy development: experiences from the South West of England

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Summary

Barriers to UK bioenergy development are understood to arise from a number of technical, financial and social constraints. A range of barriers and drivers were identified and then assessed through an online questionnaire, completed by stakeholders throughout the bioenergy industry: farmers/suppliers, developers/owners of bioenergy projects, primary end-users and government/policy stakeholders. The most critical barriers and drivers related to economic aspects of bioenergy development. It was found that farmers/suppliers and developers were influenced by production costs and benefits, whilst primary end-users of bioenergy were concerned primarily on the cost of purchasing energy. Other common drivers for all stakeholders were found to be reducing carbon emissions and the dependency on fossil fuels. This confirms that bioenergy schemes must be both economically attractive and environmentally sustainable for projects to be successful. The questionnaire demonstrates the influence and diversity between stakeholder groups which ultimately have an effect on the success of a bioenergy project.

Key Words: Bioenergy, biomass, barriers, development, drivers, South West of England.

Introduction

In response to the concerns over climate change and energy security, in 2007, the UK Government set out plans to reduce carbon emissions by 60% by 2050, with an identifiable progress by 2020 (DTI, 2007). These factors have increased attention on renewable energy. The UK Government has agreed to achieve a target of 15% of the UK's energy from renewable sources by 2020 and has acknowledged that biomass will form a significant part of this (BERR, 2008). Biomass to bioenergy is an attractive solution in reducing carbon emissions and can be applied to all forms of energy absorbing processes. The UK Biomass Strategy proposes to increase the use of biomass for heat, electricity and biofuels, and outlines the potential UK supply of feedstocks up to 2020 (DEFRA, 2007a). From the renewable energy strategy consultation it is clear that the UK bioenergy industry will need to develop significantly over the next decade if EU and UK Government targets are to be met (BERR, 2008).

In this paper a number of barriers were identified through a literature review and an assessment of different bioenergy project case studies. The various incentives, or 'drivers' for bioenergy development were also assessed. The South West of England was used for the case studies as the region is considered rich in natural resources supportive of bioenergy growth (O'Rourke, 2001). The aim of this research was to consider the main drivers and barriers that might impede

the development of bioenergy. In order to validate these barriers and drivers, a questionnaire was developed for each of the four main stakeholder groups: farmers/suppliers, developers, end-users and government/policy. Respondents were asked to assess each barrier (or driver) and rate them in importance. The objective of the research was to understand which are the most important barriers and drivers to the development of bioenergy in the UK for each main stakeholder group.

Bioenergy in context

Government-set regulations put in place in recent years have created an interest in producing energy from biomass. Electricity generation from renewable sources has been incentivised via the introduction of the Renewable Obligation. Other Government initiatives include the deployment of the Renewable Transport Fuel Obligation RTFO, (DfT, 2008). There are currently no policy drivers for renewable heat energy in the UK, notwithstanding that energy for space heating accounts for nearly half of all the UK's carbon emissions (DTI, 2007). However, the UK Government is currently considering what policy measures to introduce following the Heat Call for Evidence (BERR, 2008a).

There are a number of subsidies available within the UK to help grow feedstocks for bioenergy processes. These include the Single Payment, the Entry Level Environmental Stewardship Scheme and the Energy Aid Payment Scheme. The Energy Crops Scheme helps finance the establishment of Miscanthus and Short Rotation Coppice. A market 'push' incentive called the Bioenergy Infrastructure Scheme helps to develop biomass supply chains from harvest through to delivery to heat and power end-users, providing grants for essential, dedicated equipment such as chippers. Market 'pull' incentives have been provided by the Bio-energy Capital Grants Scheme.

Bioenergy in the South West

The South West of England is recognised to have abundant resource suitable for renewable energy technologies such as wind and biomass (RegenSW, 2003). In 2004 the Government Office for the South West (GOSW) commissioned a report examining the potential of renewable energy for the region and concluded that the region could produce between 11–15% of its electricity from renewable energy sources by 2010 (RegenSW, 2003). The South West's current renewable energy production has an installed capacity of 190MW (RegenSW, 2008).

Previous resource assessments suggest the region's combined bioenergy potential is between 537 GWh to 1,370 GWh (O'Rourke, 2001). Later studies predict bioenergy resource could rise up to 3,081 GWh per year (CSE, 2005). However, it is estimated that only around 1% of the region's total energy consumption for heat and power is derived from renewable sources (RegenSW, 2008). The lack of bioenergy development can be seen through a number of Government funded biomass energy projects that, for various reasons, experienced difficulties in implementation.

In 2004, Government funds of £18m were awarded to five bioenergy plants across the UK; four of the plants based in the South West of England (HM Government, 2007). To date, none of the projects in the region are fully operational (RegenSW, 2008). Studies carried out on some of the projects concluded a number of key reasons for unsuccessful biomass developments.

The lack of growth for bioenergy can be associated with a number of barriers. These barriers are not uncommon in other regions of the UK and in other countries. Several studies concluded a comparative pattern of barriers, which impede the development of bioenergy (Roos *et al.*, 1999; Upham & Shackley, 2006; Upreti, 2004; Upreti & Van der Horst, 2004). Literature shows that within the UK and in particular, the South West, the main barriers to bioenergy projects included:

- o Location of bioenergy plant – visual impacts (Upham & Shackley, 2006)
- o Transport increase around bioenergy plant (Upreti, 2004)
- o Mistrust between local community, developers and agencies – credibility of developer (Upham & Shackley, 2006, 2007)

- o Other environmental impacts – odours emitting etc. (McCormick & Kaberger, 2007)
- o Financial implications during operation and lifespan of plant (Piterou *et al.*, 2008)
- o Technical problems associated with conversion techniques (Piterou *et al.*, 2008)

It was apparent that barriers to the development of bioenergy differed at varying stages of project implementation. A flowchart for a typical bioenergy project is shown Fig. 1.

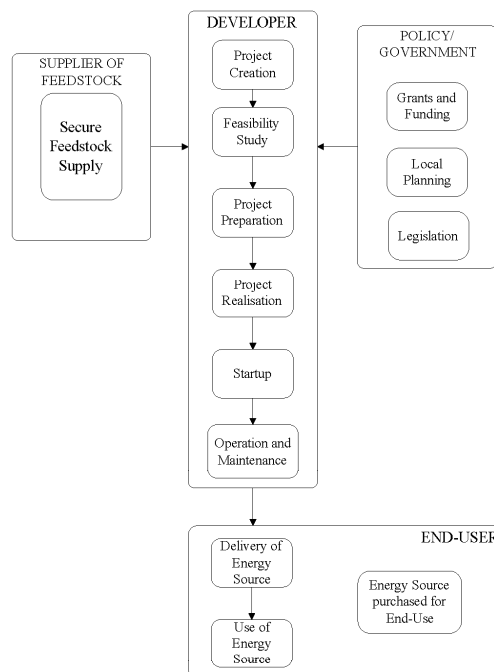


Fig. 1. Linkage between stakeholder groups for bioenergy projects – Concept from Ecofys (2005) & Deublein & Steinhauser (2008).

Methodology for identifying barriers and drivers to bioenergy development

The root causes for unsuccessful bioenergy projects can originate from any or multiple stages of the project's development chain. The supply chain, considered a critical part of the success of bioenergy development (Gill *et al.*, 2005), is ultimately created between the demand for bioenergy and the supply of the energy source. The four stakeholders that can affect a bioenergy supply chain are: supplier of feedstock, plant developer/owner, government/policy and primary end-user. Suppliers are involved in production and supply of feedstock, developers are concerned with operability and implementation of bioenergy conversion plants, whilst primary end-users purchase the primary biomass energy. Government/policy stakeholders are involved in governmental decisions regarding bioenergy in the UK.

Although four stakeholder groups were identified, bioenergy as whole was considered in the study. It was acknowledged that there were a large number of bioenergy 'pathways' and that potentially the barriers and drivers for each pathway could be different. However, the research was intended to review the barriers and drivers with a holistic approach in support of bioenergy governmental studies and strategies (DEFRA, 2007a; Gill *et al.*, 2005). Additionally, the infrastructure required to convert biomass material to bioenergy is similar whether it is specifically grown or is a by-product of another process (BERR, 2008). Therefore, an assumption is made that all bioenergy

projects will have common elements, e.g. biomass feedstock, storage, transportation, conversion technology, etc.

Having acknowledged each bioenergy pathway could have different associated barriers and drivers, the study focused on more overarching aspects of development as opposed to individual situations. Barriers and drivers for each stakeholder group were obtained from literature and case studies. The study proposed a list of possible barriers and drivers to the development, use and support of bioenergy for the four different stakeholder groups. The identified barriers resulted from extensive literature review and analysis of studies from the South West of England. The importance and links between the drivers and barriers were analysed at each stage of the bioenergy supply chain for each stakeholder group. To understand the routes of these barriers, the bioenergy development drivers were also proposed. It was acknowledged that there may be other drivers and barriers associated with bioenergy development. The study investigated the validity of these barriers and drivers for each stakeholder within bioenergy development (see Fig. 1).

Drivers and barriers for feedstock suppliers

The proposed barriers and drivers for feedstock suppliers have been illustrated in Table 1. It was understood that there could be a perceived difficulty of growing novel energy crops in comparison to other food crops (Mattison & Norris, 2007). However farmers could be willing to overcome these issues as bioenergy could offer a diverse market either from previously grown crops or able to find an alternative use of farming by-products. Low or uncertain return on investment could also be seen as an important barrier to the development of bioenergy feedstock (Sherrington *et al.*, 2008). Uncertainties of grant or funding support was also be considered a potential barrier to bioenergy feedstock. It was previously reported that without financial support the uptake of bioenergy crop production would have been considerably lower (Sherrington *et al.*, 2008). Environmental implications such as biodiversity effects and carbon reduction could also be a barrier towards feedstock development.

Table 1. *Barriers and drivers to the development of bioenergy for feedstock suppliers*

	Barriers	Drivers
Feedstock Supplier	Competition vs other established feedstocks	Attractiveness of a growing bioenergy market
	Lack of feedstock experience	Availability of financial support
	Limited/Uncertain return on investment	Good technique for waste utilisation
	Negative environmental impacts of feedstock	Market diversification
	Perceptual challenges of feedstock	Meeting governmental energy and/or waste targets
	Physical resource limitations (land availability)	Other environmental benefits (other than CO ₂ reduction)
	Resource intensive feedstock	Possible reduction in carbon emissions
	Uncertainties of financial support	Profitable return on investment
	Unclear legislative limitations	Reduction in fossil-based fuels
	Unsettled bioenergy market (unreliable buyer)	

Drivers and barriers for plant developer/owner

Proposed barriers to the development or ownership of a bioenergy project (shown in Table 2) included adopting a conversion technology that could either be financially or practically unproven.

These were considered valid across the board of bioenergy pathways. Other barriers included a lack of local feedstock supply, forcing developers to import from outside the UK. The import of wood-pellets into the UK signifies the lack of feedstock supply within the country (Junginger *et al.*, 2008). Financial considerations also offered a number of potential drivers and barriers to the development of bioenergy projects. Proposed drivers for bioenergy included the Governmental support mechanisms. However uncertain financial costs associated with operation, maintenance of bioenergy plants and costs of distribution of bioenergy were also anticipated to be a significant barrier (Piterou *et al.*, 2008).

Table 2. *Barriers and drivers to the development of bioenergy for plant developers/owners*

	Barriers	Drivers
Plant Developer/Owner	Competition vs other renewable energy options	Availability of financial reward/support mechanisms
	Lack of feedstock supply	Bioenergy supply consistency vs. intermittent energy options
	Low primary-end-user demand	Bioenergy use versatility
	Perceptual challenges of bioenergy plant	Increase bioenergy interest from end-user
	Planning and Installation Issues	Market diversification/opportunity
	Possible negative environmental impacts	Possible reduction in carbon emissions
	Uncertain development and operational costs	Reduction in fossil-based fuels
	Uncertainty of conversion technology/equipment	Variety of feedstock use for bioenergy. Resource diversification
	Unclear and complex legislative issues	

Drivers and barriers for primary end-user of bioenergy

The primary end-users of bioenergy were understood to include a wide range of users from electricity suppliers requiring ROCs to domestic heating users wanting to reduce dependency of fossil-based fuels and improve environmental impacts associated with energy use. The associated barriers (Table 3) included financial implications of bioenergy. High buying costs of bioenergy with respect to other source of fossil-fuel derived energy or even other renewable energy options was thought to potentially discourage the buying of bioenergy. Similarly, uncertainties within the bioenergy market and seasonal variability of feedstock supply would ultimately create volatile buying costs for various types of bioenergy.

Drivers and barriers for government/policy

Table 4 shows the barriers and drivers affecting government/policy stakeholders and relate to how this group would support the use and development of bioenergy. Barriers in financial support mechanisms may be a result of unproven conversion technologies that would ultimately not provide a valid return on investment. Support mechanisms may also be affected by the environmental benefits or disbenefits of bioenergy use.

Other barriers proposed for this stakeholder group included the competition that bioenergy could face versus other renewable energy options, such as wind energy or solar. Another barrier could be derived from the link between bioenergy crop growth and the rise in food crop prices. Sourcing feedstock from unsustainable sources could have negative implications on the environmental benefits of using bioenergy, which could ultimately hinder government-set targets of carbon reductions, and increasing fuel security (DTI, 2007).

Table 3. *Barriers and drivers to the development of bioenergy for primary end-users of bioenergy*

	Barriers	Drivers
Primary End-User	Bioenergy costs vs fossil-fuel	Ability to penetrate most energy markets
	Infrastructure and other costs	Bioenergy use consistency vs. other intermittent energy options
	Legislative issues	Direct Substitute of fossil-based fuels
	Low supply of bioenergy	Good technique for waste utilisation
	Perceptual challenges of bioenergy use	Help in supporting Governmental schemes
	Preferential over other renewable energy options	Investment opportunity into renewable energy
	Seasonal effects of bioenergy supply	Positive effects on Image
	Uncertainty of adaptability	Possible reduction in carbon emissions
	Unsettled/Changing bioenergy market	Reduction in fossil-based fuels

Table 4. *Barriers and drivers to the development of bioenergy for Government/Policy stakeholders*

	Barriers	Drivers
Government/Policy	Competition vs. other renewable energy options	Bioenergy supply consistency vs other intermittent energy options
	Lack of feedstock supply Resource Availability	Bioenergy use versatility
	Legislative Issues regarding bioenergy	Decentralisation of energy capability
	Negative effects on food crop prices	Good technique for waste utilisation
	Negative global environmental impacts	Increase rural development and economy
	Negative local environmental impacts	Increased fuel security
	Perceptual challenges	Possible reduction in carbon emissions
	Uncertainty of conversion technology/equipment	Reduction in fossil-based fuels
		Variety of feedstock use for bioenergy.
		Resource diversification

Stakeholder survey for barriers and drivers to bioenergy

Having proposed the main barriers and drivers for each stakeholder group, a stakeholder survey was prepared. Stakeholders also had the opportunity to add other barriers or drivers which they thought had not been mentioned in the survey. The stakeholders for each group were obtained through a number of bioenergy-related events attended during 2007–2008. The stakeholder's suitability was assessed based on previous experience or a relevant interest in the bioenergy field.

In order to survey the stakeholder groups, an online questionnaire was constructed. Stakeholders were asked how important each barrier and driver was for the development of bioenergy. The questionnaire offered the candidates five choices: 'critical' importance, 'very' important, 'moderate' importance, 'unimportant' or undecided. The stakeholders were contacted via emails with a

covering document explaining the details of the research. The email enclosed a web link directing them to the online survey. Once the questionnaire was completed, the respondent submitted the information, stored in an online database. The data was then be collated and analysed to determine the most important barriers and drivers to bioenergy development.

Results

A summary of the key findings from the stakeholder surveys is shown. All results are given as percentages (%) of respondents who stated that the barrier (or driver) was of ‘very’ or ‘critical’ importance. Only the most important barriers or drivers are included in the results. The response rate of the questionnaire was just over 45%, with a total of 72 responses.

The most significant barrier to the development of bioenergy projects for farmers and suppliers was found to be competition from other crops (85%). The next most significant barrier was the uncertainty of grant and funding (75%). Return on investment (64%) and availability of land (57%) were also seen as important. The only ‘other’ barrier identified by respondents was the risks associated with long term contracts. Making a profit was the most important driver for farmers and suppliers (90%). Reducing dependency on fossil fuels was the next most important driver (75%), closely followed by reducing carbon emissions (71%) and the growing bioenergy market (67%).

Technology was identified as the most important barrier by developers (84%). Development and operational costs were the second most significant barriers (76%). Legislative issues (64%) and resource availability (58%) were also seen as important. Of the ‘other’ barriers identified by respondents the most important one was the uncertainty over, or lack of, grant funding. Financial reward and support was the most important driver (91%). Market opportunity was the second most important driver (82%) followed by reducing dependency on fossil fuels (68%); reducing carbon emissions (64%); and constant supply of energy (64%).

High buying costs with respect to fossil fuels was the biggest barrier by considerable margin (88%). Legislative issues were chosen as the second most important barrier (73%) followed by new infrastructure requirements (67%), insufficient supply availability (67%), and uncertainties of adaptability (57%). Other barriers identified were lack of vehicle manufacturer support, e.g. warranties being voided on biodiesel blends greater than 5%; difficulties securing long term contracts for feedstock; lack of new technology demonstration projects; and insufficient knowledge or experience of bioenergy.

Reducing dependency on fossil fuels was the most important (86%) driver followed by the direct replacement of particular fuels (83%), reducing carbon emissions (71%), good utilisation of waste (69%), and constant supply of energy (58%). The relative cost of bioenergy in comparison to fossil fuels was identified as being an increasingly important ‘other’ driver.

In comparison with the other stakeholder groups, the barriers for Government and Policy were much more evenly distributed. The most important barrier was resource availability (62%) followed by unproven technologies (56%), rises in food crop prices (53%), and legislative issues (53%). There were several ‘other’ barriers identified by respondents. The most important of these was the lack of skilled or trained workers in the bioenergy field. Reducing dependency on fossil fuels (88%) and reducing carbon emissions (81%) were the most important drivers, followed by increased fuel security (69%) and good utilisation of waste (63%). The increasing price of oil and other non-renewable fuels was identified by several respondents as an important other driver.

Discussion

The questionnaire results show that both the barriers and drivers are different for each stakeholder group, with some commonalities. The diversity of bioenergy systems means that some care

needs to be taken when interpreting results, however all bioenergy systems comprise of the four stakeholder groups. The results give useful insights as to the most important barriers and drivers to the development of bioenergy schemes.

Competition from other crops was seen as the most important barrier primarily because, at present, annual food crops remain more economical than perennial energy crops. Financial return on investment and market volatility are also important barriers due to the potential impacts on a farm's business structure. The availability of land is important as farmers are likely to grow energy crops on their least productive land. Making a profit was by far the most important driver and underpins the significance of energy crops and other biomass feedstock needing to be economically viable. Farmers and suppliers also identified climate change and fossil fuel dependency as imperative, which is not surprising given their close working relationship with nature, and reliance on fuel for machinery. These findings are consistent with a recent study on the domestic supply of perennial energy crops (Sherrington *et al.*, 2008).

The use of unproven or commercially unviable conversion technologies was identified as the most important barrier, possibly due to a number of failed or slow developing bioenergy projects in the UK. However, when compared to other EU countries it is apparent that for many bioenergy production pathways, technology is not seen as an important barrier (McCormick & Kaberger, 2007). Development and operational costs are important as the logistics of biomass systems require feedstocks and their conversion to be inexpensive in comparison to fossil fuels. High capital costs are also associated with most bioenergy technologies. Legislative issues are an important barrier for developers as they need to be familiar with a range of legislation and regulations depending on the technology. Compliance with legislation can be complex and costly.

Feedstock resource is essential as markets face competition from other industries. In particular, energy crops face direct competition for land from food crops. The fuel supply chain was identified as a key barrier by RCEP and the Biomass Task Force (RCEP, 2004; Gill *et al.*, 2005). Developers increasingly need to devise a flexible approach to feedstock supply in response to changing market conditions.

Consumers and businesses will make consumption decisions based on the buying cost; the instability of bioenergy costs demonstrates this as the most important barrier. The development of bioenergy is therefore highly dependent on the cost in comparison with fossil-based fuels. Legislative issues were important, which is perhaps a reflection of the various types of legislation which affect different aspects of bioenergy. New infrastructure requirements are an important barrier; examples include new biomass heat installations, storage requirements, or vehicles requiring engine alterations to accept higher levels of biofuel blending (Hammond *et al.*, 2008). This new infrastructure will require capital investment and may not always be practical or economic.

Reducing dependency on fossil fuels, directly replacing particular fuels for bioenergy and reducing carbon emissions were the most important drivers. This is understood as end-users increasingly notice the implications of shifting oil, electricity and gas prices and there is increased awareness of climate change and energy security.

Resource availability was significant as a barrier as reliance on imports to meet targets means that the sustainability of the biomass resource is being questioned. To make a significant contribution to the UK energy supply, this group considered new conversion technologies as essential. In the case of biofuels, the Gallagher review found that new advanced technologies are immature, currently expensive and require specific incentives (RFA, 2008). This can be similar for other bioenergy pathways.

The lack of skilled or trained workers in the bioenergy field was identified as important. In comparison to more developed bioenergy industries, such as in Germany, Austria or Finland, the UK lacks sufficient installers, operators, maintenance engineers, and the like. A large increase in skilled bioenergy workers will be required if the UK is to meet its renewable energy targets. This has also been highlighted in previous reports (Gill *et al.*, 2005; BERR, 2008). The most important drivers found from the survey coincide with recent Government strategies, such as the Energy

White Paper (DTI, 2007), Waste Strategy for England (DEFRA, 2007*b*), and the UK Biomass Strategy (DEFRA, 2007*a*).

Several links have been identified between the barriers of different stakeholder groups. Economic barriers are common across the whole supply chain. The three most critical barriers for suppliers all relate to economics. Developers have identified development and operational costs and grant uncertainty as very important. End-users biggest barrier is the high buying costs with respect to fossil fuels. Technology barriers are also common across some stakeholder groups. Developers and Government/policy have rated unproven conversion technologies as a critical barrier. Environmental impacts are generally seen as being of low or moderate importance barriers in all stakeholder groups. Reducing carbon emissions and dependency on fossil fuels was the main link between the drivers for all stakeholder groups, which is critical when considering the sustainability of bioenergy. However, suppliers and developers both rated economic drivers as being of critical importance. This is understandable as both groups are businesses and rely on profit for survival.

It was acknowledged that with any questionnaire, there will always be an element of bias. Potential issues include the description of each barrier or driver, the way which the questions are worded, the order in which they are numbered, the stakeholder's background or point of view, or the sample size. The authors attempted to address these potential issues during the design of the questionnaire. For example, the survey allowed each barrier and driver to be rated in importance; a clear description was given for each barrier or driver; the questionnaire was only sent to individuals who were known to have key experience in the bioenergy industry. However, individual interpretations were beyond the authors' control.

Conclusion

Opportunities for utilising bioenergy pathways are both numerous and diverse. This research identified the key drivers and barriers for each of the four main stakeholder groups associated with bioenergy systems. Each stage of the bioenergy supply chain has unique barriers and drivers, which demonstrates the importance of consulting with all stakeholder groups when planning a bioenergy project or policy. Several of the most important barriers and drivers identified were economic. It was found that farmers/suppliers and developers made decisions based primarily on production costs and benefits, whilst end-users made decisions based primarily on the cost of purchasing energy. Consequently, bioenergy schemes must be economically attractive for projects to be successful, and for bioenergy to fulfil its potential. Given that one of the most common drivers for all stakeholders is to reduce carbon emissions and dependency on fossil fuels, the net energy and carbon benefits of bio-energy schemes must also be proven. Developers, end-users and government/policy stakeholders identified insufficient supply and resource availability as important barriers. This highlights the need for supply-chain development and co-ordination for all bioenergy pathways (RCEP, 2004; Gill *et al.*, 2005).

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A bioenergy resource assessment for the south west of England

G. P. Hammond, M. C. McManus and W. G. Mezzullo

Bioenergy will need to play a significant role in the future of Europe's energy provision in order to maintain energy security and sustainability. In this context, a regional assessment of biomass availability for energy use has been carried out for the south west region of England. Current bioenergy production, the maximum present resource availability and the maximum available future feedstock (at around 2020) in the region have been evaluated on the basis of a resource flow analysis. Extensive agricultural land (over 80% of the total land cover) and optimum climatic conditions of the region make it favourable for bioenergy feedstock development. Nevertheless, the slow uptake of bioenergy technologies has resulted in only modest feedstock growth and supply. Bioenergy production in the region at present is comparatively low at around 1300 GWh (approximately 4.32 PJ) of primary energy, with a significant portion of this resource being recovered from waste. It is therefore argued that a shift towards the use of perennial crops is desirable, along with increased farm-waste energy recovery. The regional bioenergy potential by around 2020 is estimated to be 5500–13 800 GWh (20–50 PJ) of primary energy, which would provide 4–9% of the region's primary energy consumption.

1. INTRODUCTION

Issues relating to the UK's energy direction have increased over the past decade as a result of concerns over climate change and energy security. In May 2007, the UK government set out a strategy to maintain energy security and assist a change to a low carbon economy. The strategy includes energy saving, the development of cleaner energy supplies and ensuring that clean energy supplies are economically competitive.¹ The push for clean energy supplies has focused mainly on electricity generation, space heating and transport. A target of 10% renewable electricity generation supply by 2010 has been set, with an aspiration to double this value by 2020.¹ National renewable heat targets have yet to be put in place, however work has been undertaken to reduce the carbon impact of heat generation in the UK.²

Bioenergy, thought to have a high potential within the UK, could be significant in meeting the government's energy targets. The implementation of biomass technologies within the current energy mix would not only reduce carbon emissions but could also improve energy security if fuel were produced locally.

However, biomass production may result in a reduction of food availability and cause other issues with unknown results, such as expansion of monocultures.^{3,4} In some cases, the use of bioenergy may only offer little, if any, carbon savings when the whole life cycle of some bioenergy pathways is considered.⁵

With an acknowledged ignorance of the potential for biomass as an energy source, in 2005 the Biomass Task Force⁶ set out proposals for accelerating the use of biomass within the UK. Two years later, the government produced a biomass strategy with the aim of meeting the proposals set by the task force.⁷ The strategy indicated that biomass energy production in the UK could be enhanced by

- sourcing an additional 1 million oven-dry tonnes (ODT) of wood per annum in England by developing currently unmanaged woodland and increasing the recovery of wood for energy from managed woodland
- increasing perennial crop production for biomass in the UK with the potential to use up to a further 350 000 ha across the UK by 2020,⁸ capable of yielding around 3.5 million ODT of miscanthus per year (assuming miscanthus yield of 10 ODT/ha per year)
- increasing the supply and management of organic waste.⁹

The south west region of England is considered to have high natural resources complementary to renewable energy requirements, in particular wind energy and biomass. Consequently, regional renewable electricity targets were set higher than the national average at 11–15% by 2010.¹⁰ The South West's large agricultural land area, comprising over 80% of the total available land, makes it an attractive location for perennial energy crop production. Managed woodland accounts for around 43% of total woodland in the region, with scope for increase in woodfuel availability. The region's extensive farming capacity demonstrates potential for the supply of organic waste.

The purpose of this research was to determine the biomass resources currently and potentially available in the south west region on a material flow basis. An assessment of biomass production was undertaken in order to determine the availability of bioenergy within the region. Resource assessments to date have considered bioenergy development to be limited in contributing to regional renewable energy targets,¹¹ mainly because of the financial constraints of adopting various technologies. Previous regional resource assessments have considered biomass energy supply for heat

and power only, excluding the use of bioenergy for transport. This study differs as it examines all bioenergy feedstocks, including waste streams and dedicated biomass crops. The analysis also highlights the contrast between actual production and maximum achievable production, including an analysis of future potential for bioenergy development.

The resource assessment highlights bioenergy potential in terms of primary energy. For readily combustible feedstocks such as agricultural crops, energy crops, and woodland and forestry resources, this is determined by examining the net calorific value of a feedstock. However, for wastes such as farm wastes and municipal solid waste (MSW) the primary energy value of the biogas potential was considered for the resource assessment. The calorific content of biogas was subsequently used to account for bioenergy potential.

Although conventionally biogas is considered as a secondary biomass source, in this study it was regarded to be a primary energy source as

- (a) the majority of current energy from waste in the south west region is collected through biogas production and generally is the most accepted form of energy recovery from waste
- (b) the use of biogas from farm waste enables the waste to be used as a natural source of fertiliser, thus not affecting current end use of manures
- (c) biogas is considered a renewable energy source and is defined as a primary fuel according to the *Digest of United Kingdom Energy Statistics*.¹²

This approach examines the total primary energy potential regardless of its end-use energy application; it therefore does not consider whether the resource is used for electricity generation, heat or transport use.

2. BIOENERGY IN THE SOUTH WEST

Relative to other UK regions, the South West has a wetter climate and generally warmer temperatures. These conditions favour agricultural development in terms of animal and crop farming. The region's woodland was estimated to have the greatest woodfuel biomass resource potential in England, with around 24% of the country's total woodfuel potential supply.¹³

Land use in the region is heavily dominated by agriculture, with just under 1.9 million ha allocated to farming. This is significant as biomass generation is similar to food crop farming and can be adapted around existing rural economies. For example, anaerobic digesters are best placed in close proximity to animal and food waste and are therefore suitable for use within the farming sector. Previous resource assessments suggest the region's annual bioenergy resource potential in terms of primary energy is 537.5–1370.1 GWh.¹⁴ Other studies predict that bioenergy resources could rise to 3081 GWh per year. Scholes¹⁵ estimated that miscanthus and short-rotation coppice (SRC) energy crops had supply potentials of up to 27.5–114.0 MW (228.9–948.7 GWh primary energy). The assessment undertaken here examined current production and use of bioenergy, current maximum potential availability and maximum future potential availability for all biomass resource types. The results were compared with previous resource assessments.

3. BIOMASS RESOURCE TYPES AND CONVERSION TECHNOLOGIES

Biomass is defined as biological matter derived from living or recently living organisms, including plant-based and animal-derived material. Plant-based biomass is formed via photosynthesis, converting energy from the sun into chemical energy stored within the organic material.¹⁶ Chemical energy within biomass can be stored for long periods and then extracted through a series of techniques (Figure 1).

Biomass for bioenergy production can be categorised as primary or secondary source, different from primary and end-use energy. Primary biomass is organic material that can be used immediately in its organic form, such as wood for combustion. Secondary biomass is obtained in the form of solids, liquids or gases and is available for use subsequent to a conversion process.¹⁷ This study recognised the energy potential of a bioenergy feedstock in its primary source for non-waste feedstocks and secondary source for waste types.

Bioenergy conversion techniques vary depending on resource availability, conversion technology adopted and end-use requirements. Conversion techniques can be grouped into three types: thermochemical, biochemical/biological and physical-chemical.¹⁸

3.1. Thermochemical conversion processes

- (a) Gasification – a high-temperature conversion process. Biomass is heated to an elevated temperature with a limited supply of oxygen. The use of oxygen as a gasification medium leads to high calorific values for the end-use gas. Due to dilution by nitrogen, a lower calorific value of gas would be obtained with the use of air only. The product gas (a mixture of carbon monoxide, carbon dioxide, hydrogen and methane) is produced and ignited. Feedstocks for this process include herbaceous perennial grasses, woody perennials and residues, and waste. The remaining residue is biochar, which can be used as fertiliser.
- (b) Pyrolysis – a high-temperature conversion process. Biomass is heated to a high temperature without the presence of oxygen. The remaining residue is carbon. Pyrolysis creates a combination of bio-oils, biogas and char, depending on the reaction conditions. Feedstocks for this process include herbaceous perennial grasses, woody perennials and residue, and waste.
- (c) Combustion – ignition of biomass to recover thermal energy. The thermal energy produced can be converted into mechanical energy or electricity or simply used as heat. Most feedstocks are acceptable for this conversion process provided the moisture content of the material is less than 50%.

3.2. Biochemical conversion processes

- (a) Fermentation – the conversion of carbohydrates into alcohols or acids through a biochemical process. The process is usually carried out under anaerobic conditions, but this can vary depending on the feedstock used. Most types of biomass feedstocks can be used for fermentation, provided sugars such as glucose, fructose and sucrose are present. The most common type of fermentation process is the production of bioethanol from sugar or starch crops.
- (b) Enzymatic hydrolysis – involves a chemical reaction that converts raw feedstock cellulose chains into glucose, which

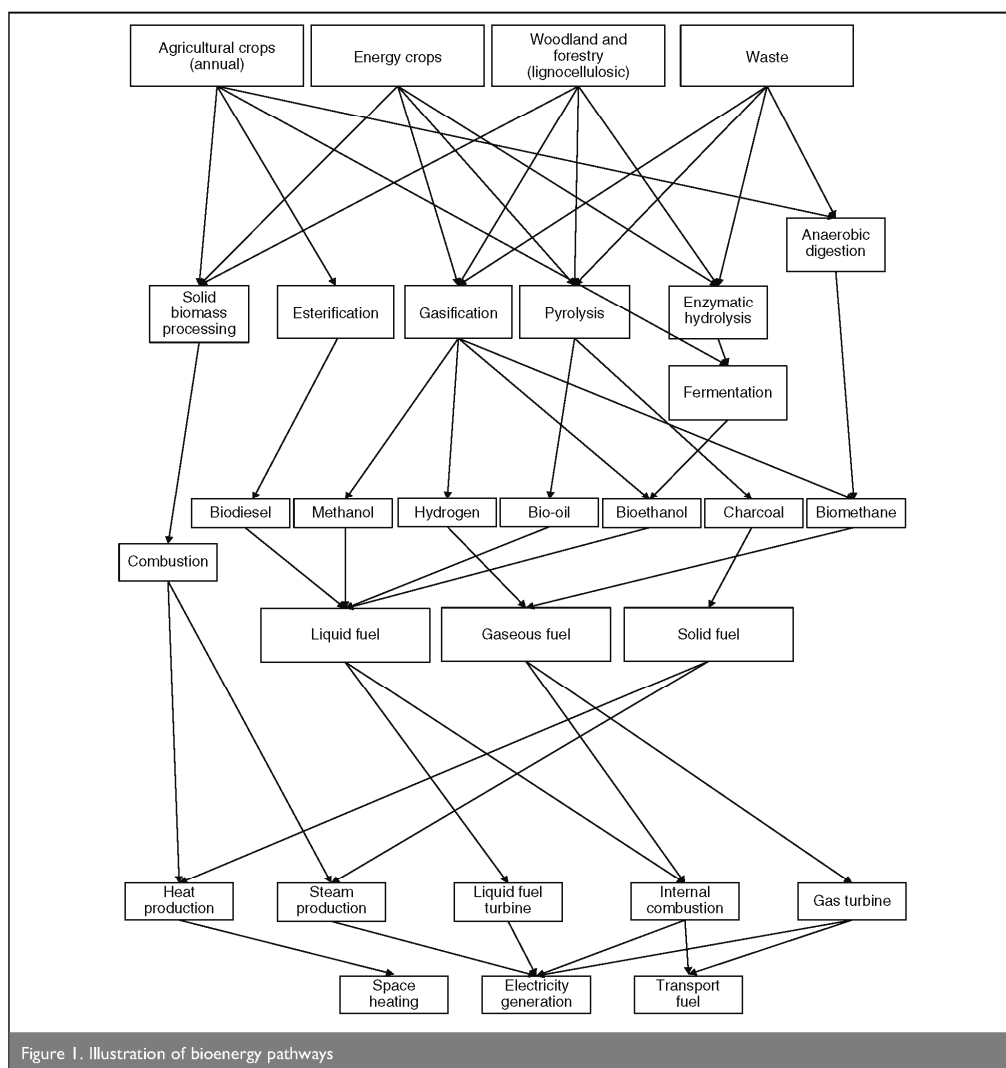


Figure 1. Illustration of bioenergy pathways

can then be fermented for bioethanol production. The process allows woody biomass feedstocks to be converted into liquid biofuels.

- (c) Anaerobic digestion – the conversion of organic material into biogas. Biogas is produced from the decomposition of organic material in the absence of air. The biogas produced is a mixture of methane (50–75%) and carbon dioxide. Biogas can be used in a variety of combustion processes and is a direct replacement for natural gas. Feedstocks tend to be animal- and human-produced wastes, including MSW; however, any biomass feedstock is suitable.

3.3. Physical-chemical

Esterification is the process of recovering oil from biomass crops. The oil is converted into biodiesel using an esterification process in which an alcohol is reacted with the oil. Biodiesel can, in most cases, be used as a direct substitute for benchmark

petrodiesel; however, due to its increased acidity it can have higher corrosion levels. Feedstocks for this conversion process include oil-based biomass such as oilseed rape, peanuts, sunflower seeds. After purification, waste cooking oils can also be used.

4. METHODOLOGY

A quantified resource assessment for the south west region was carried out to determine bioenergy availability in the region. Generally, previous resource assessments have adopted a top-down estimate of bioenergy. The terminology top-down signifies that the primary considerations of a resource assessment include economic viability, technology availability followed by resource availability and land-use development; however, these can vary depending on their priority. The assessment carried out here adopted a bottom-up methodology. Material flow resource analysis was primarily considered. This

was then followed by placing market allocations, economic limitations and sustainability constraints on the resource results.

The methodology adopted for estimating bioenergy potential from different sources involved determining the calorific value of each bioenergy feedstock. The calorific value would then give a valid representation of the primary energy potential. For bioenergy feedstocks such as wood-biomass, where moisture content values can be reduced, the calorific value is a valid representation of the primary energy available. For feedstocks with higher moisture contents, such as organic waste and animal manure, it was assumed that suitable fermentation processes would be used (e.g. anaerobic digestion). The calorific content of biogas generation from fermentation was then used to account for bioenergy production.

Biomass resources can be divided into two main categories – wood biomass and non-wood biomass. The technique described by Rosillo-Calle¹⁹ was tailored for the South West bioenergy resource assessment. This type of methodology allows easier and quicker categorisation of different types of biomass, which is useful as biomass has a large number of different feedstock types and can be converted to a range of end-use energy types.

Wood plant species are characterised by slow growth and tightly knit fibres.²⁰ Wood biomass is organic material containing ligneous matter and comprises

- (a) forest and woodland residue
- (b) lignin-type and SRC energy plantations (although miscanthus is defined as a herbaceous plant species, it was considered to be woody as it can be used for combustion; the lignin content of miscanthus is approximately 17%, while that of willow, a type of SRC, is around 19%)
- (c) arboriculture plantations.

Non-wood biomass comprises herbaceous materials but also includes wastes from organic materials. The main categories are

- (a) agricultural crops
- (b) crop residue
- (c) herbaceous crops
- (d) processing residue
- (e) animal waste
- (f) other waste, for example MSW, commercial and industrial (C&I) waste.

Upon completion of data collection for various biomass feedstocks, constraints were placed to distinguish between actual and potential biomass supply. The potential supply is the maximum possible biomass resource currently available, disregarding any constraints or limitations. Actual supply incorporates constraints and limitations. Due to data availability, only physical, financial, market and accessibility constraints were taken into account in this work. Constraints that could affect biomass availability are¹⁹

- (a) environmentally sustainable accessibility – that is, examining whether obtaining biomass causes environmental damage or is not sustainable
- (b) financial accessibility – that is, examining the cost of accessing biomass (e.g. the need for expensive equipment or time taken to collect biomass are limiting factors);

financial implications to suppliers are also linked to this constraint

- (c) physical accessibility – that is, examining whether obtaining biomass is physically possible
- (d) climatic constraints – wind speeds, water availability, and so on can have a limiting effect on biomass availability
- (e) land quality – that is, assessing the suitability of land to determine whether a certain crop can be grown
- (f) market constraints – some biomass may already be allocated to other markets (e.g. furniture)
- (g) technology limitations – some technologies may not be available within the region.

4.1. Assessment of wood resources

The data collection methodology for the wood resource assessment is illustrated in Figure 2. This process covered all geographical areas of wood biomass and the data were used to assess quantity and quality (availability) of biomass resource. The investigation was grouped into three areas: energy plantations, agro-industrial and processed biomass.

Energy plantations include dedicated energy plantations such as SRC and miscanthus, and woodland and forest areas. Agro-industrial plantations comprise farm wood residue, and arboriculture residues, such as shrubs, hedges, etc. On-farm woodland is generally managed by farmers, but ever-increasing restrictions on farm waste are opening a potential for biomass.²¹ Arboriculture arisings are woody wastes suitable for bioenergy, produced by tree surgeons conducting maintenance on gardens, road and rail verges.

Figure 2 summarises the key data sources. Primary data were obtained from the Forestry Commission data. Other sources included the following.

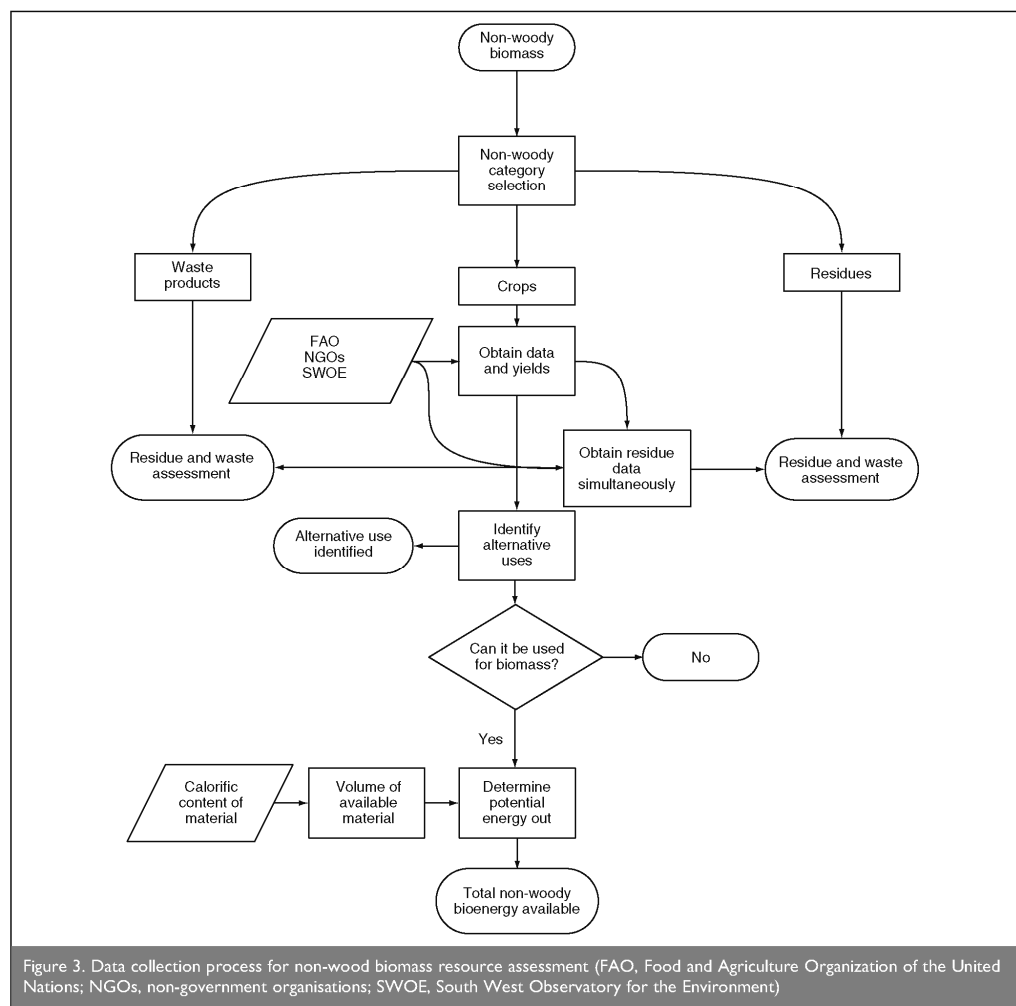
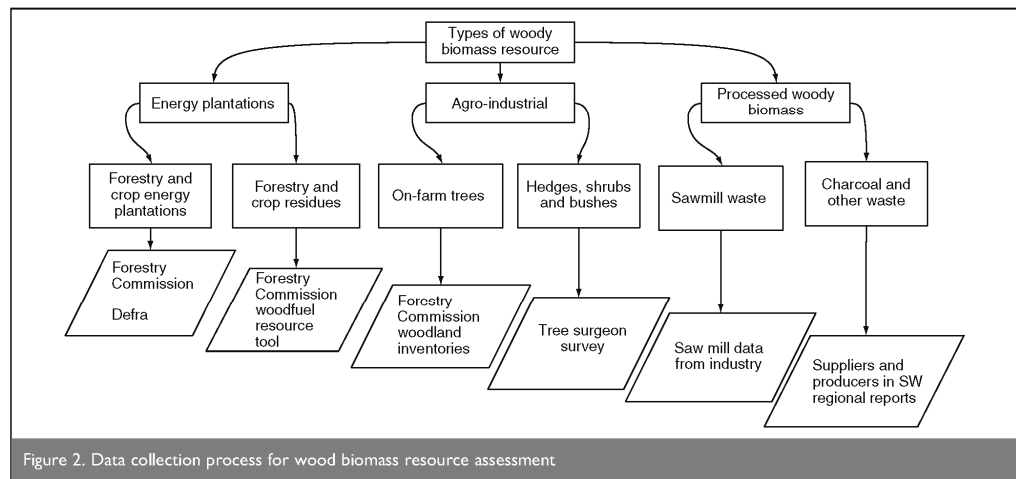
- (a) Tree surgeon survey. Information was gathered by creating a database of tree surgeons operating in the South West and surveying a sample to determine annual waste wood production for the region.
- (b) Sawmill survey. Yield data were derived from sawmills in the South West using a method similar to the tree surgeon survey.
- (c) Current woodfuel consumption data from other sources, including Regen South West, the Renewable Energy Association and other regional organisations.²²

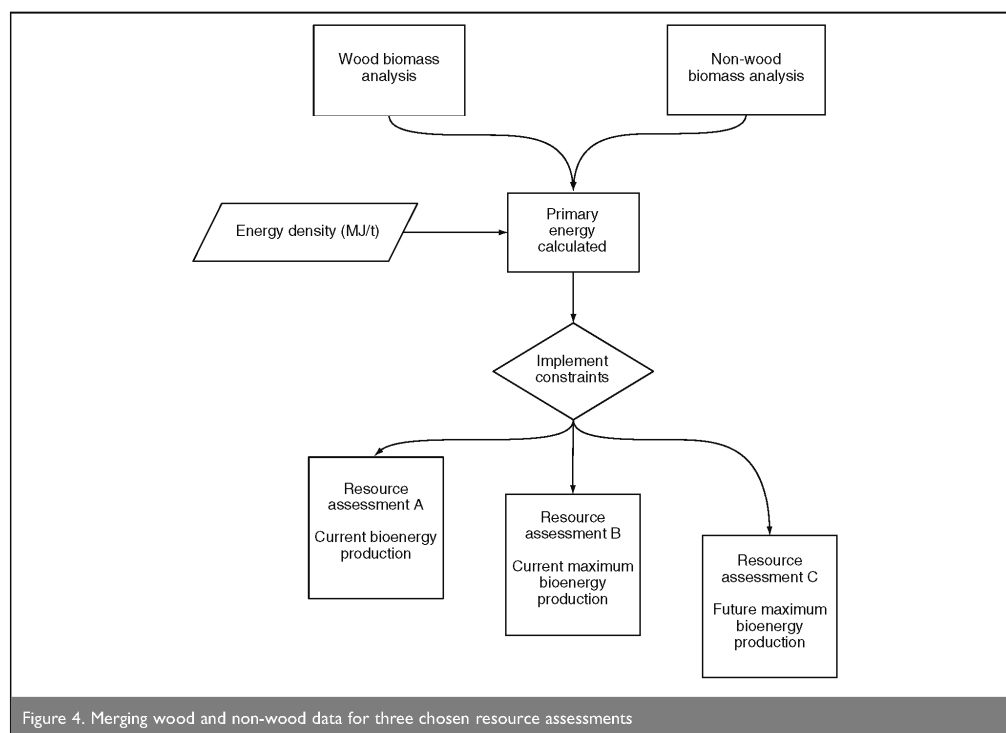
4.2. Non-wood resource assessment

The total available non-wood biomass was also estimated. For the purpose of this research, non-wood biomass is defined as¹⁹

- (a) agricultural crops (wheat, sugar beet, oats, etc.)
- (b) residues from farming crops (e.g. straw, processing slurry)
- (c) herbaceous annual and perennial crops (plants with stems that die at the end of the growing season)
- (d) animal waste, including poultry litter, cattle and pig slurry, which can be used to make biogas or can be incinerated
- (e) other waste, for example MSW and C&I waste.

Figure 3 shows the data collection process for the non-wood biomass resource assessment, initially divided into herbaceous crops, waste products and crop residues. The waste analysis was then expanded further to incorporate different types of waste including plant residues, animal waste and other waste. The





data for this section were obtained from the Department for Environment, Food and Rural Affairs (Defra) and the Environment Agency (EA). Waste data including MSW and C&I waste were collected from various regional reports and other data sets.^{23–25}

4.3. Combining resource assessments

The resource collection methodologies for wood and non-wood analyses of bioenergy potential were then adapted for various bioenergy resource assessments. These were considered as different levels of bioenergy implementation within the region. The three assessments are as follows.

- Resource assessment A: assessment of current bioenergy production and use in the south west region. This involved recording all current bioenergy-dedicated crop growth and operational bioenergy plants with feedstocks from within the region.
- Resource assessment B: assessment of the current theoretical maximum bioenergy potential in the region. This involved examining the maximum bioenergy potential on a material-based analysis followed by implementing a series of constraints on the results.
- Resource assessment C: assessment of the future maximum bioenergy availability. This involved looking at the feedstocks in scenario B and determining whether these could increase over the next ten years. Consideration was given to possible crops to be grown on available land and increased adoption of anaerobic digestion.

Primary energy for each feedstock was calculated using energy density values obtained from the literature^{19,26} and

constraints were put in place, as shown in Figure 4.

Although no specific energy end-use technology was used for the study, it was assumed that the bioenergy feedstock would filter into a number of established bioenergy conversion techniques within the region. Organic farm waste, for example, was assumed to be converted into biogas. Biogas in this case was considered as the primary energy source, as mentioned previously. However, primary energies from other feedstocks such as woodfuel and energy crops, which can be used for a range of commercially viable conversion technologies, were calculated using net calorific energy values per ODT.

5. RESOURCE ASSESSMENT RESULTS

5.1. Resource assessment A: current bioenergy production

This assessment examined current bioenergy production in the South West and incorporated all sources of bioenergy feedstocks. Energy from waste (landfill gas, sewage, farm biogas and other forms) was found to be currently the largest contributor to bioenergy in the region, accounting for 56% of total bioenergy use (Figure 5). The majority of the energy produced from waste is derived from landfill gas across 22 sites within the region. The largest landfill-gas energy recovery plant in the South West is situated in Dorset (Whites Pitt) and has a power rating of 6.92 MW. Landfill sites have a larger energy capacity (due to the size of the biomass resource available) than sewage-gas energy plants, which do not generally exceed 1 MW in electricity generation.

The analysis showed current bioenergy production in the South West to be 1300 GWh (4.32 PJ), equivalent to approximately

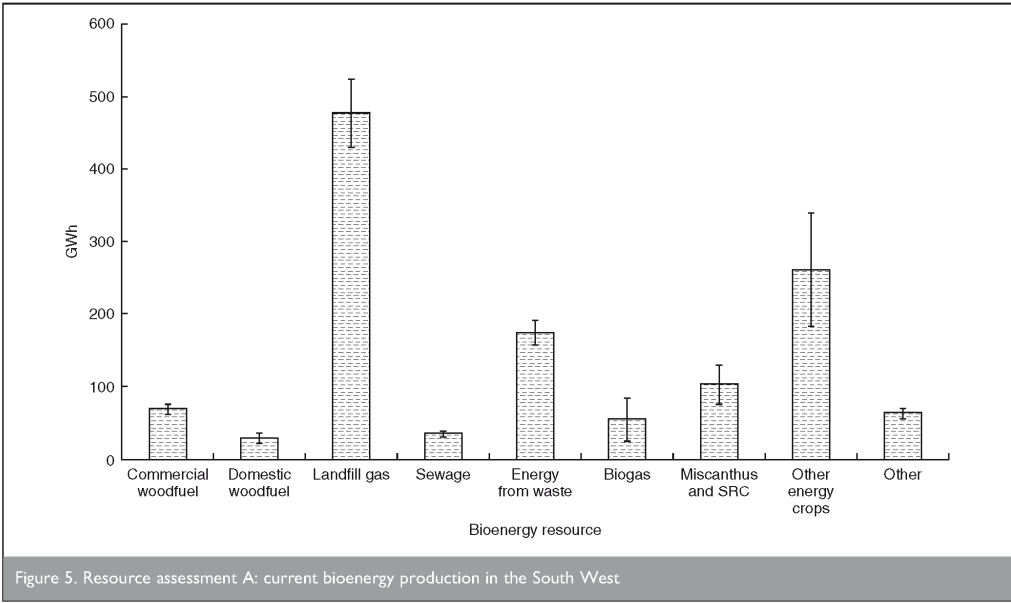


Figure 5. Resource assessment A: current bioenergy production in the South West

160 MW of power. Converting energy content (MWh) to power (MW) is roughly equivalent to

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$$\begin{aligned} &\text{expected output or required input (MWh)} \\ &= \text{power (MW)} \times \text{plant operational time} \\ &\quad \times \text{capacity factor} \end{aligned}$$

Typical biomass plant operational time can vary between 7500 and 8500 h annually, depending on plant downtime and operational load.^{15,27} The capacity factor is the ratio of the actual output of a power plant per unit time and its output if it had operated at full capacity per unit time. For electricity generation from gasification and pyrolysis, typical capacity factor values are around 80–90%.¹⁵ However, ultimate energy delivery can also be affected by operational downtime of conversion plants and variation between designed and actual operating capacity.

Biodiesel production in the South West is relatively new as oilseed rape is currently generally used for animal and human consumption. However, the renewable transport fuel obligation states that, by 2010, 5% of the volume of transport fuel must be sourced from biofuels.²⁸ However, this target is intended to be pushed back to 2013/14 after concerns regarding the uncontrolled expansion of the use of biofuels raised in the Gallagher review.²⁹ Therefore, biodiesel and bioethanol production supply is expected to increase. The UK's largest biodiesel plant is to be built in the region within the coming years and is proposed to ultimately produce up to 500 000 t of biodiesel per year.³⁰ This is equivalent to 5138 GWh of energy per year; however, the source of the feedstock for this plant is unclear and was therefore not considered in this study.

Biogas from anaerobic digestion of farm manure accounts for 4% of total bioenergy production in the South West (Figure 6). A number of plants are situated in rural locations across the region, where animal and food waste is readily available.^{31,32} Woodfuel contributes to 8% of the bioenergy mix in the South West. Woodfuel is used mainly for heating, as it is considered too costly for electricity generation alone. The lack of managed woodland and limited plants within suitable transport distances represents significant barriers to woodfuel growth.

5.2. Resource assessment B: current maximum available bioenergy resource

The maximum available bioenergy potential represents the theoretically obtainable fuel that could be used for bioenergy production: currently not marketed as a resource or where current markets could be altered in order to allow bioenergy

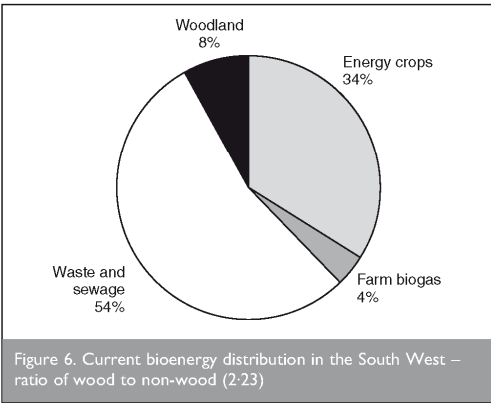


Figure 6. Current bioenergy distribution in the South West – ratio of wood to non-wood (2:23)

generation. This study did not consider altering food or timber production markets, but analysed bioenergy on a material flow basis by assessing the availability of material suitable for bioenergy. Possible end-use energy applications, such as electricity generation, heat production or transport energy use, were not considered. The assessment examined all possible feedstocks suitable for bioenergy.

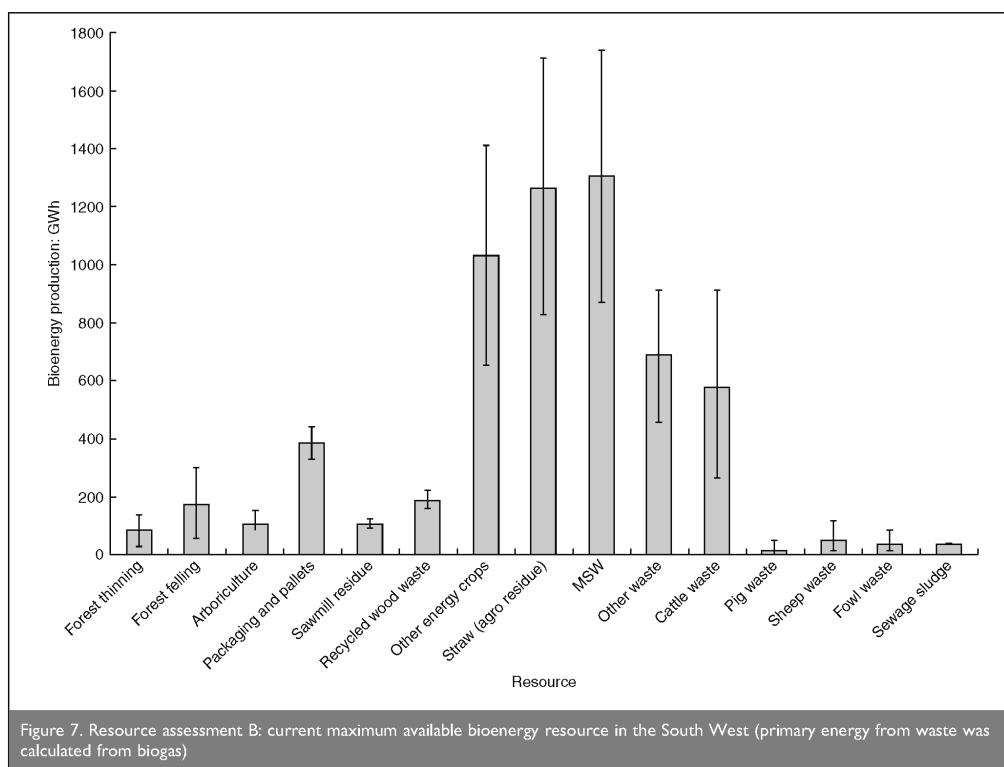
One of the key constituents in assessment B was the use of straw for bioenergy. Straw is a by-product of wheat, barley, oats and rye production. The main source of straw in the South West is from wheat and barley grown on over a quarter of a million hectares within the region. The assessment considered an uptake of 30% of straw for bioenergy, as this could be readily available if straw prices were competitive. This portion of straw could be derived either from currently sold straw or a blend from different sectors of straw use.

Straw is currently used within the farming sector as follows: 40% is ploughed back into land to improve soil fertility and structure; 30% is baled for farmers' own use; and 30% is sold.³³ Other reports suggest that around 45% of total straw produced in the UK is either burnt or ploughed back into fields.³⁴ However, the 1993 Crop Residue Burning Regulations ban straw burning after harvest.³⁵ Ely, near Cambridge, is home to the world's largest straw-burning power facility. The unit produces 270 GWh of energy per year from an intake of around 200 000 t of straw. The UK is reported to produce over 15 Mt of straw per year; according to the Department for Business, Enterprise and

Regulatory Reform, 50% of this could feasibly be used for energy production.³⁶

Straw is considered commercially viable for bioenergy if priced between £25/t¹¹ and £35/t³⁷ (approximately £6500–£9000/GWh based on a calorific value of 4.1 MWh/t), dependent on plant scale. Prices in May 2007 were £38.43/t (£9753/GWh) for baled wheat straw and £25/t for big square-baled wheat straw.^{38,39} Prices in July 2008 for the same two straw types were recorded by Defra to be £40/t and £34/t (£10 152/GWh and £8629/GWh) respectively.³⁹ However, straw prices were as low as £20/t (£5076/GWh) in 2006, thus showing cost is dependent on seasonal climate. Other factors affecting straw prices include annual yield output and costs incurred during production (e.g. fuel costs). The assumption of 30% straw intake for bioenergy gives 1300 GWh of primary energy potential. This value accounts for straw cultivated from wheat and barley, using a straw production constant of 5 t/ha.

Significant bioenergy potentials for assessment B included energy from waste (Figure 7). This source of energy accounted for over a third of the potential supply of bioenergy in the region. MSW and other wastes could offer between 1325 and 2650 GWh of primary energy from biogas.²⁴ This calculation assumed that the wastes had an organic content of 60% and methane production from landfill would be 40–80 m³ per tonne of organic waste, in accordance with similar resource assessments.⁴⁰ However, a regional waste strategy for the South West (published in 2004) underlined the necessity of effective



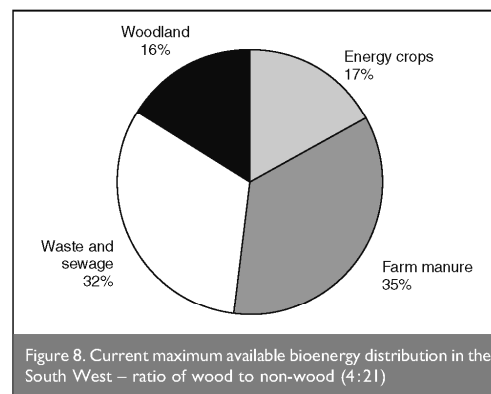
waste minimisation²⁴ and various policies aiming to reduce waste generation in the region have been implemented. Landfill tax, packaging regulations and the 2003 Waste and Emissions Trading Act contribute to the reduction in waste generation. This could therefore potentially reduce the availability of bioenergy from waste sources.³⁷

Other sources of available bioenergy include dedicated energy crops such as miscanthus and SRC grown on set-aside land. Using data obtained by Defra, these were found to be low in number in comparison with non-set-aside energy plantations. Only miscanthus and SRC on both set-aside and non-set-aside land were considered due to the availability of data. Energy crops were calculated to produce up to 1000 GWh using the land currently allocated to bioenergy in the region. (Land availability for the expansion of energy crops and future potential supplies are considered in the next section.) In 2007, however, energy crops on non-set-aside land (denoted other energy crops in Figure 5) greatly outweighed crops grown on set-aside land, as farmers are able to choose which land provides the greatest return on their investment.

Energy crops grown on arable land could become more common within the region as farmers are able to obtain competitive annual returns for energy crops as well as food crops. In 2005, the Common Agricultural Policy was reformed and all individual payment schemes were replaced with one single payment with more of a focus on land stewardship. The aim of this was for farmers to grow a greater choice of crops based on the highest annual return, thus opening up the potential to use land for energy crop purposes.⁴¹ Energy crop grants are essential for crops such as miscanthus and SRC to be economically viable. These crops were estimated to cost in the region of £40–60/ODT (£8000–12 000/GWh) for SRC production and £32–44/ODT (£6800–9400/GWh) for miscanthus production.⁴² However, it has been reported that acceptable purchasing prices for power generation would be around £25/ODT, thus making energy crop payment supplements essential.¹¹

Energy from animal waste could provide a significant portion of the bioenergy mix. Cattle waste, if processed effectively, can offer up to over 670 GWh (2.41 PJ) of energy per year, adopting a conservative estimate of 50% of the animal manure intake. However, variables in methane production and calorific values show that animal waste has the largest variability of any energy production. The bioenergy supply available from animal waste would involve an intake up to 20% of total animal waste production in the South West (derived primarily from cattle, pig and poultry waste); this figure was assumed in accordance with other regional reports.¹¹ Total UK manure production in 2005 was calculated to be approximately 88 Mt; around 30% of this was liquid slurry,⁴³ which is considered to be an ideal feedstock for anaerobic digestion.

Presently, biogas production is considered economically unfeasible when operating solely on farm waste. Generally, a combination of farm waste and industry food waste is utilised as additional income is generated through gate fees (the fee charged, per tonne of waste, by a waste receiver to the waste producer⁴⁴). However, gate fees do not apply to farm waste as they can be used directly as fertiliser. Studies show that biogas generation is cost-effective for both electricity and heat



generation if the plant receives a minimum of £30/t in gate fees for all waste collected.³⁷ This would create a financial incentive for biogas development and would not limit the feedstock to industry food waste.³²

There are significant benefits in adopting a 20% uptake of animal waste for production of biogas. Currently, animal manure is ploughed directly back into fields as a form of natural fertiliser. However, the digestate from anaerobic digestion of animal waste is suitable as a fertiliser and in some cases has advantages over undigested slurries and manure as it offers a consistent nutrient concentration.⁹ Therefore, a scenario of 100% adoption of animal waste for biogas production should not be overlooked if anaerobic digestion plants were to become economically feasible, through grants or funding.

In contrast with current bioenergy production shown in assessment A, woodfuel has a much higher potential for bioenergy production (Figure 8) subject to extensive woodland and forest management. Approximately 463 382 ODT of biomass wood per year could potentially be available as woodfuel,¹³ including all stemwood, tips, branches, foliage and poor-quality wood. However, of this amount, 330 000 ODT is currently already marketed for other timber products and is considered unlikely to be used for bioenergy.⁴⁵ Therefore, the largest woodfuel resource type is arboriculture arisings, followed by small roundwood and branch wood from forestry.⁴⁶

The available woodfuel comprises woodland residue and wood processing waste. This type of woodfuel could become a potential resource for bioenergy if it were economically feasible. Woodfuel, as a sole fuel, is considered economically unviable for electricity generation and therefore should only be considered for heat production, co-firing purposes or combined heat and power (CHP) systems.³⁷ Due to woodfuel's low energy density, a larger quantity of feedstock is required to produce an electrical energy output equivalent to other fossil-based fuels such as natural gas or coal. For this reason, woodfuel is suitable for lower-temperature energy uses such as space heating, where operating temperatures are much lower. The costs of woodfuel vary significantly, from £40/ODT (£7500/GWh) for logs to £110/t (£22 000/GWh) for wood pellets. Studies show that wood used in woodchip form for heat generation is one of the most cost-effective uses for wood as a bioenergy source.³⁷

The calculated bioenergy resource availability in the South West was estimated to be 3891–8420 GWh (14.07–30.31 PJ), which could contribute 2.6–5.5% of the region's energy use. Although this is a theoretical maximum potential, it is significantly higher than current bioenergy production (around 1300 GWh), possibly because of a series of technical and non-technical constraints.⁴⁷

Technological limitations and varying government support at both regional and national level are also possible causes for relatively low bioenergy use compared to the region's actual capability.⁶ When assessing the maximum theoretical bioenergy resource, the increase in available potential was a result of relatively straightforward changes to market reallocation. For example, straw use and animal waste management was altered in line with recent government strategies,⁷ as opposed to reducing food production and creating competition for land use. Therefore, as the data show, current bioenergy production in the South West could be increased significantly without an increase in new biomass production. However, there are uncertainties in the economic and environmental impacts associated with these changes.

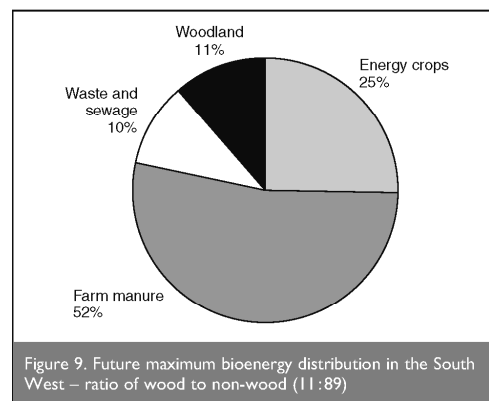
5.3. Resource assessment C: future maximum available bioenergy resource

Analysis of the South West's bioenergy potential showed a considerable increase in future potential compared with the current maximum availability. The analysis considered a scenario up to 2020, as data are generally available up to this date. Studies such as RE-vision 2020,¹¹ Rubbish to Resource²⁴ and Stepping Forward²³ have all set targets for 2020. This also meets government plans to cut carbon emissions by 60% by 2050 with real progress by 2020.¹ This analysis also examined the total primary energy available from potential biomass feedstocks within the region, using forecasts of land use, waste management and woodland use projected in the literature.^{11,23,24}

The analysis showed that bioenergy potential could be as high as 5508–13 809 GWh (19.82–49.71 PJ). The bioenergy potential increased further from the second analysis due to maximisation of animal waste and exploitation of arable land considered suitable for bioenergy crop growth.⁴⁸ In the past, set-aside land accounted for 2.5% of the total farmed agricultural land available in the region. This corresponds to approximately 46 340 ha of land – the equivalent of supplying around 148 000 t of biodiesel or 370 000 t of bioethanol, approximately 5% of the UK's requirement to comply with the renewable transport fuel obligation by 2010.

Other land available considered suitable for biomass is grassland under five years old.⁴⁸ This type of grassland in the region accounts for over 200 000 ha – more than four times the land area allocated in 2007 for set-aside use. Although set-aside land in 2008 was set to 0%, it was made clear that the decision would only be taken for that year.⁴⁹ Surveys carried out in early 2008 estimated that only 40% of set-aside land and bare fallow land would be used by farmers, leaving the rest uncropped.⁵⁰

Eliminating set-aside land and thus increasing the available land for farm use could enable farmers to grow more profitable energy crops as well as food crops. However, the high wheat prices recorded for 2007–2008 (peaking at just under £120/t) could

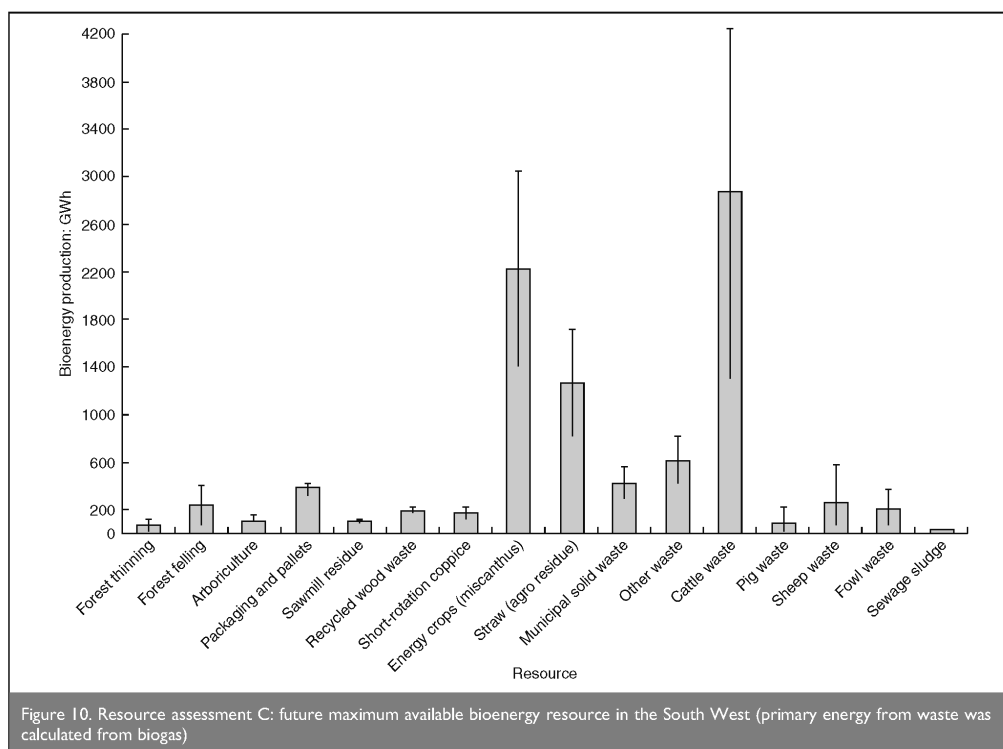


result in farmers growing wheat for food rather than energy crops. The study concluded that energy crops could be grown on a land area equivalent to that of set-aside land between 2006–2007; at approximately 57 000 ha, this accounts for less than 2.7% of total farmed land in the region. The change in total farmed area from 2002 to 2006 increased by 112 000 ha; therefore a bioenergy uptake of 57 000 ha was considered not to have serious impacts on current food production in the region.

The use of energy crops in the South West could offer considerable biomass resource potential for energy production. The findings showed that although there is a lower contribution from MSW and C&I waste, overall bioenergy potential is still higher than the current maximum potential. This highlights the region's potential in moving away from 'uncontrolled' sources of bioenergy (such as waste generation) to more 'controlled' production, such as energy crops (Figure 9). This suggests that the region has the capability of producing bioenergy from controlled direct sources rather than a secondary process such as the recovery of energy from waste. Dedicated energy crops and managed woodland are imperative in the supply of consistent bioenergy resources as they will maintain a steady source of resource material.

The analysis also indicated that bioenergy dependence on waste could gradually reduce, as shown in Figures 9 and 10. It was assumed that MSW and C&I waste would be reduced due to increased recycling and stringent regulations imposed on landfill sites.²⁴ Figure 10 shows that the total accountable bioenergy from MSW, other wastes and sewage could account for 1402 GWh per annum (equivalent to 5.04 PJ/year). The region's waste strategy states that 'by 2030 the region will become a minimum waste producer'²⁴ and confirms proposals to reduce waste. Although landfill gas is considered a renewable energy source in terms of grant acceptability, waste incineration is only recognised as a renewable source if the waste is purely biomass (subject to a maximum fossil-derived energy content of 10%); mixed waste would therefore not be considered as a renewable energy source. However, energy from waste operated through a CHP unit is eligible for renewable obligation certificates (ROCs).

In contrast to energy from waste, bioenergy from woodfuel in the South West is predicted to remain constant until 2021;



predictions from Forestry Commission studies indicate little or no increase in available woodfuel biomass until 2021.⁴⁵ Further analysis indicates actual wood availability (not available woodfuel, but that used for timber manufactured goods) in the region increasing by approximately 100 000 ODT/year over the period 2003–2021. Woodfuel supply from Forestry Commission owned woodland in the South West is expected to reduce, while a greater proportion will come from privately owned woodland.⁴⁵ This is thought to be a result of the growing market for woodfuel becoming more financially attractive.

The bioenergy potential of animal waste was calculated using a theoretical waste intake of 100% for biogas processing – that is, all animal waste produced for half of the year in the South West would undergo anaerobic digestion treatment. However, the entire uptake of farm waste for biogas production is unlikely as it would require networking all the farms in the region across a series of biogas generation facilities. Under current practices, the contribution of gate fees for non-farm waste makes this approach economically unviable. However, if animal waste for bioenergy were to increase, this would ultimately provide a much higher feedstock rate to the plants, thus increasing the biogas potential in the bioenergy mix³² and reducing the need for food processing waste.

6. ANALYSIS OF RESULTS

The future bioenergy potential for the South West is higher than the current maximum potential, with capabilities for increased capacity over a range of feedstocks. MSW and C&I waste volumes are predicted to decrease; with a stable animal farming

population in the region over the past seven years, the main increased future supply of bioenergy therefore relies on maximising usage of arable land and exploiting existing farm waste. Table 1 highlights the increase between the three resource assessments.

One reason for the increase in potential bioenergy supply is linked to utilisation of available arable land. The use of this land is important in achieving the highest bioenergy yield with the least significant impact on other commercial crops. It was therefore necessary to find the optimum energy crop and crop use suitable for the region. Given the available arable area, miscanthus combustion was found to be the highest energy producer (Figure 11). The analysis was based on crop yield alone and did not take into account costs or other externalities. The production of biodiesel from oilseed rape was one of the least efficient choices for land use in terms of net energy output. Energy from biogas proved to produce around half the energy output of miscanthus combustion. Biogas is a versatile bioenergy form that can effectively replace natural gas and can operate using a range of biomass feedstocks. Although Table 2 shows combustion of miscanthus for bioenergy to be the most effective, limiting bioenergy to one type of crop and one conversion process would reduce feedstock diversification.

The abundance of bioenergy resources in the region is apparent, predominantly from resource assessments B and C. These analyses envisage maximum possible energy output available based on the feedstock calorific values. All calculated values for bioenergy resources have an associated error value between

	Primary energy supply			
	Minimum		Maximum	
	GWh	PJ	GWh	PJ
Resource assessment A	1074	3.86	1470	5.29
Resource assessment B	3891	14.07	8420	30.31
Resource assessment C	5508	19.82	13 809	49.71

Table 1. Bioenergy resource production and availability for the three resource assessments

Crop	Total primary energy: MWh	Energy per unit area: MWh/ha per year
Miscanthus	3 529 380	61.10
Oilseed rape (biodiesel)	292 863	5.07
Short-rotation coppice	2 079 504	36.10
Wheat (bioethanol)	556 267	9.63
Wheat (biogas)	1 098 671	19.02
Barley (biogas)	223 547	3.87
Fodder beet (biogas)	1 568 870	27.16
Forage maize (biogas)	1 734 075	30.02
Hemp (biogas)	805 230	13.94
Oats (biogas)	186 578	3.23
Sugar beet (biogas)	1 504 175	26.04

Table 2. Primary energy production for various crops on available land (57 000 ha) in the south west of England^{15,26}

which the overall output can deviate. All calculated bioenergy outputs would ultimately offer lower net energy values at the end-use stage. Therefore, it is important to distinguish between primary energy content and net energy contribution for each feedstock.

7. DISCUSSION

This study indicates that the potential for bioenergy production in the South West is high. The prospects for significantly increasing current uptake are good, primarily due to the region's extensive agriculture sector, although high resources of woodland and waste generation will also favour an increase in bioenergy. However, improved woodland management displays little benefits in terms of bioenergy increase.

It is apparent that bioenergy is not being fully maximised in the region, mainly because of economic and technical constraints raising the cost of bioenergy deployment. Public perception of bioenergy plants has created severe obstacles for planners and developers and this has halted plant implementations across the region. For example, the 21.5 MW biomass gasifier site in Winkleigh, Devon^{51,52} and the north Wiltshire 5 MW wood gasification plant^{47,53} both failed as a result of public opposition.

The low levels of bioenergy implementation in the South West can be linked to other unsuccessful renewable energy attempts in the region. The fundamental problems lie with the cost considerations of these technologies. At present, mainstream energy production techniques are cheaper, more abundant and readily available. In addition, there is relatively little or no pressure for consumers to opt for 'greener' technologies such as wood-fired domestic boilers or household micro-CHP because the cost of implementing such systems is not returned at current fuel prices.

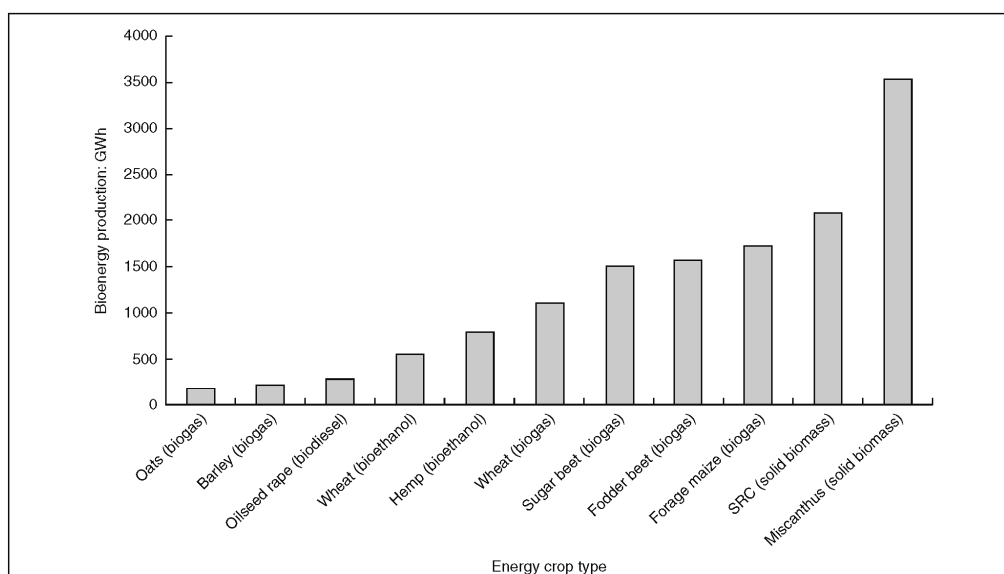


Figure 11. Bioenergy production potential on available crop land for the South West

Although there are no regulations or financial incentives to produce heat from renewable sources, electricity suppliers in the UK are now obligated to source a percentage of their energy from renewable feedstocks; this is supported by ROCs.⁵⁴ Energy suppliers can choose their source of renewable energy used to obtain a ROC, but this could limit the use of bioenergy as it can be more expensive than other renewables. However, following a recent government consultation, ROCs are to be banded by 1 April 2009. This will allow emerging technologies such as anaerobic digestion, gasification and pyrolysis to be worth 2 ROCs/MWh, while energy from landfill gas will be worth 0.25 ROCs/MWh;⁵⁵ the price of a ROC at the time of writing is £35.76.

Assuming bioenergy production for heating was to be subsidised similarly to electricity generation, there could potentially be an increase in uptake of biomass for heat. In addition to this, bioenergy feedstock is generally available in rural areas, thus making it attractive for the South West. However, expensive transport costs due to its low energy per volume or mass make it less attractive in urban areas. This could be overcome, however, by transporting biomass in other forms such as wood pellets, pressurised biogas or bioliquids (bio-oils, biodiesel and bioethanol). These routes should be investigated further.

The results of resource assessment C indicate that the maximum contribution from bioenergy sources in the South West could be just under 14 000 GWh of primary energy per year. In particular, energy crops from what was once set-aside land and other permanent grassland could contribute to up to 2600 GWh per year based on primary energy assumptions. This agrees with findings from previous resource assessments for the South West¹⁵ in which calculations for bioenergy from energy crops revealed a minimum potential contribution of just under 3000 GWh.

However, bioenergy from energy plantations is accountable for only a portion of the bioenergy mix. For significant development in bioenergy, all feedstocks should be considered. The adaptability of biomass feedstock favours the approach of adopting multiple conversion techniques for bioenergy as opposed to a mono-conversion bioenergy system.

In 2001, domestic, industry and service sectors in the South West consumed 152 000 GWh of energy.²³ Resource flow scenarios for 2015 based on no energy efficiency measures predicted that domestic energy consumption would rise by 4.5%. Adopting this figure for all energy sectors, this would result in an energy consumption of around 159 000 GWh by 2015.²³ Using the values calculated in Table 1 and adopting resource assessment C, bioenergy could offer 4–9% of total energy use in the region. The use of bioenergy alone could thus meet the South West's renewable electricity targets.¹⁰ This study also highlights the considerable potential of bioenergy in the region's energy mix using currently available feedstocks (resource assessment B). The South West's main sector for energy use is currently domestic, where bioenergy could be used for electricity and heat (Table 3).

Table 3 shows the contribution that bioenergy could make towards the region's primary energy use, based on resource assessment B (3891 GWh and 8420 GWh). If used solely for the domestic sector, this could contribute 5–12% of the region's

Sector	Primary energy consumption in 2001		Bioenergy potential adopting resource assessment B: %	
	GWh	PJ	Minimum	Maximum
Domestic	71 762	258.3	5	12
Industry	24 912	89.7	14	33
Services	55 111	198.4	6	15

Table 3. Bioenergy contribution for each sector based on resource assessment B

energy, while for the industry sector alone this could be 14–33%. The diversity of bioenergy could potentially result in a mix contribution towards all three energy-use sectors as opposed to accounting for one alone. However, a problematic situation could arise if a particular bioenergy route were to become more profitable than the rest. This would result in potential single or limited use for bioenergy determined primarily by economic return on investment.

8. CONCLUDING REMARKS

The wealth of bioenergy resources in the south west region of England offers good potential in pursuing targets set in the UK's biomass strategy in which biomass has an important role within the renewable energy mix.⁷ Government plans include modifying and strengthening the renewable obligation scheme in order to decrease direct competition with renewable energy types, while favouring all biomass types. Other incentives include increasing the energy crop content in biomass co-firing from 25% for 2009 and 75% for 2016; co-firing will cease to be eligible for ROCs from 31 March 2016.⁵⁶

The resource assessments showed that the majority of energy recovery from biomass was currently energy from waste, from either landfill gas or waste incineration. The bioenergy shift could move towards perennial and improved farm manure management as these two biomass branches will offer greater economic returns than energy recovery from waste in the future. Municipal and other waste types are also set to reduce in availability as a result of recycling and capping waste generation per household. The region's abundant resources of biomass indicate that technological development could be advanced. Economic constraints should, according to the UK biomass strategy, pose fewer issues due to funding mechanisms currently available.

It can be concluded that slow development is not dependent on obtaining resources for bioenergy production, as the results display positive potential for feedstock supply within the region. The South West has extensive arable land availability and optimum climatic conditions for bioenergy feedstocks. However, the slow uptake of bioenergy technologies has resulted in low stimulation of bioenergy feedstock growth and supply.

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APPENDIX E

MISCELLANEOUS

Screenshots of barriers & drivers questionnaire

Barriers and Drivers to Bioenergy in the UK - Government / Policy						Exit this survey >
3. Drivers to Bioenergy						
<p>★ 1. The following DRIVERS have been identified as key drivers in the development of bioenergy projects.</p> <p>Thinking about how important each driver is to the development of bioenergy, in your opinion, rate the following drivers as either:</p> <ul style="list-style-type: none"> - Critical Importance - Very important - Moderate importance - Unimportant - Undecided <p>If you think there are other key drivers(s) that are not included above, please provide a brief description below.</p>						
	Critical Importance	Very important	Moderate importance	Unimportant	Undecided	
Reduction in Carbon Emissions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Increased Fuel Security / Reduced Energy Imports.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Increase in rural economy and employment, e.g. operating plant and growing feedstock in rural areas.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Constant supply of Energy vs. other renewable options, e.g. availability and storage of feedstock.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Decentralisation of Energy Economy, eg. primary energy can be obtained from various locations.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Reducing Dependency on Fossil-based fuel.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Good Utilization of Waste.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Capability of penetrating every energy sector, e.g. bioenergy conversion processes allow diverse fuel types.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Resource availability diversification, i.e. Bioenergy conversion processes are able to use many feedstocks.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Barriers and Drivers to Bioenergy in the UK - Government / Policy						Exit this survey >
2. Barriers to Bioenergy						
<p>★ 1. The following BARRIERS have been identified as key barriers in the development of bioenergy.</p> <p>Thinking about how important each barrier is to the development of bioenergy, in your opinion, rate the following barriers as either:</p> <ul style="list-style-type: none"> - Critical Importance - Very important - Moderate importance - Unimportant - Undecided <p>If you think there are other key barriers(s) that are not included above, please provide a brief description below.</p>						
	Critical Importance	Very important	Moderate importance	Unimportant	Undecided	
Unproven Technology, e.g. commercially unviable, lack of knowledge and experience, immature market, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Resource Availability, e.g. lack of feedstock, land available, water resources, energy intensive, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Competition, e.g. similar bioenergy projects, securing feedstock, other renewables, low demand, high selling price.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Global Environmental Impacts, e.g. energy intensive production, long transport distance, biodiversity, land use change, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Local Environmental Impacts, e.g. soil/water/air quality, biodiversity, visual/noise /odour, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Rise in food crop prices.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Legislative issues, e.g. EU Directives, CAP, International standards, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	
Perceptual Challenges, e.g. negative local opinion, environmental/visual challenges, increased transport, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	

Barriers and Drivers to Bioenergy in the UK - End Users

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2. Barriers to Bioenergy

* 1. The following BARRIERS have been identified as key barriers for the end-users in the development of bioenergy.

Thinking about how important each barrier is to the development of bioenergy, in your opinion, rate the following barriers as either:

- Critical Importance
- Very important
- Moderate importance
- Unimportant
- Undecided

If you think there are other key barriers(s) that are not included above, please provide a brief description below.

	Critical Importance	Very important	Moderate importance	Unimportant	Undecided
High buying costs with respect to fossil fuels.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Uncertainty of adaptability, e.g. blending biodiesel or bioethanol, co-firing, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Seasonal Variability of Fuel, depends on crop and availability.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Legislative issues, e.g. Govt policy decisions, International standards, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Public Perception Challenges, e.g. customers may not want bioenergy.	<input checked="" type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
New/Unsettled/Changing Bioenergy Market.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
New Infrastructure Required.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Other Renewable Technologies Established, e.g. wind, solar.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Insufficient Supply available	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Barriers and Drivers to Bioenergy in the UK - End Users

[Exit this survey >](#)

3. Drivers to Bioenergy

* 1. The following DRIVERS have been identified as key drivers for end-users in the development of bioenergy projects.

Thinking about how important each driver is to the development of bioenergy, in your opinion, rate the following drivers as either:

- Critical Importance
- Very important
- Moderate importance
- Unimportant
- Undecided

If you think there are other key drivers(s) that are not included above, please provide a brief description below.

	Critical Importance	Very important	Moderate importance	Unimportant	Undecided
Direct Replacement of Particular Fuels.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Improved Company Image.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reduction in Carbon Emissions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Constant supply of Energy vs. other renewable options, e.g. availability and storage of feedstock.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reducing dependency on rising fossil-based fuel.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Versatile Fuel Options, e.g. Bioenergy conversion processes allow diverse fuel types.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Supportive of Renewables Obligation (ROC) and Renewable Transport Fuel Obligation (RTFO).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Good Utilisation of Waste (if applicable)	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
New Market Gap - investment in diversification of renewables.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Barriers and Drivers to Bioenergy in the UK - Developers

[Exit this survey >](#)

3. Drivers to Bioenergy

* 1. The following DRIVERS have been identified as key drivers for developers in the development of bioenergy projects.

Thinking about how important each driver is to the development of bioenergy, in your opinion, rate the following drivers as either:

- Critical Importance
- Very important
- Moderate importance
- Unimportant
- Undecided

If you think there are other key drivers(s) that are not included above, please provide a brief description below.

	Critical Importance	Very important	Moderate importance	Unimportant	Undecided
Financial Reward/Support, e.g. Bioenergy Capital Grants Scheme, Renewables Obligation, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Market Opportunity, e.g. profit motive, new business.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reduction in Carbon Emissions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Constant supply of Energy vs. other renewable options, e.g. availability and storage of feedstock, Primary energy can be obtained from various locations.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reducing dependency on Fossil-based fuel.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Capability of penetrating every energy sector, e.g. Bioenergy conversion processes allow diverse fuel types.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Resource availability diversification, i.e. Bioenergy conversion processes are able to use many feedstocks.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Increased Interest and Demand from end-users.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Barriers and Drivers to Bioenergy in the UK - Developers

[Exit this survey >](#)

2. Barriers to Bioenergy

* 1. The following BARRIERS have been identified as key barriers for developers in the development of bioenergy.

Thinking about how important each barrier is to the development of bioenergy, in your opinion, rate the following barriers as either:

- Critical Importance
- Very important
- Moderate importance
- Unimportant
- Undecided

If you think there are other key barriers(s) that are not included above, please provide a brief description below.

	Critical Importance	Very important	Moderate importance	Unimportant	Undecided
Technology, e.g. commercially unviable, unproven technology, lack of knowledge/experience.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Resource Availability, e.g. lack of feedstock, land available, water resources, energy intensive.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Competition, e.g. similar bioenergy projects, securing feedstock, other renewables, low demand, high selling price.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Environmental Impacts, e.g. energy intensive production, long transport distance, biodiversity, land use change, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
End User Demand, e.g. low demand, other energy sources, compatibility of product.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Local Planning, e.g. large building, unknown technology, Pollution Prevention Control (PPC).	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Development and Operational Costs, e.g. bad planning, lack of experience, immature markets, high set-up costs.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Legislative issues, e.g. Govt policy decisions, International standards, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Perceptual Challenges, e.g. Negative Local Opinion, Environmental/Visual Challenges, increased transport, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Barriers and Drivers to Bioenergy in the UK - Farmers/Suppliers

[Exit this survey >](#)

3. Drivers to Bioenergy

* 1. The following DRIVERS have been identified as key drivers for farmers/suppliers in the growing of bioenergy crops.

Thinking about how important each driver is to the development of bioenergy, in your opinion, rate the following drivers as either:

- Critical Importance
- Very important
- Moderate importance
- Unimportant
- Undecided

If you think there are other key drivers(s) that are not included above, please provide a brief description below.

	Critical Importance	Very important	Moderate importance	Unimportant	Undecided
Reduction in Carbon emissions.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Good utilisation of waste, e.g. anaerobic digestion, use as natural fertiliser.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Market Diversification, e.g. new business, innovative way to use land and diversify income.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Grant and Funding availability, e.g. energy crops scheme, non-food crops, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Making a profit.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Growing Market, e.g. increasing demand for energy crops.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Reduced dependency on fossil fuels.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Perennial crops preferable, e.g. lower maintenance once established.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Belief in the environmental benefits of bioenergy production.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
To help meet Govt targets for renewable energy.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

Barriers and Drivers to Bioenergy in the UK - Farmers/Suppliers

[Exit this survey >](#)

2. Barriers to Bioenergy

* 1. The following BARRIERS have been identified as key barriers for farmers/suppliers in the growing of bioenergy crops.

Thinking about how important each barrier is to the development of bioenergy, in your opinion, rate the following barriers as either:

- Critical Importance
- Very important
- Moderate importance
- Unimportant
- Undecided

If you think there are other key barriers(s) that are not included above, please provide a brief description below.

	Critical Importance	Very important	Moderate importance	Unimportant	Undecided
Insufficient Experience / Equipment e.g. commercially unviable, unproven technology, lack of knowledge, lack of experience, unproven crops, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Resource, e.g. energy intensive, cost of fertiliser, water, equipment, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Return on Investment, e.g. expensive to set-up, 3 year delay, low selling price.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Grant and funding uncertainty, e.g. EU have reduced single payment, energy crops scheme, set aside.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Competition for other crops, i.e. Other (food) crops more economical.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Land availability.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Volatile Market, e.g. failed market, insufficient demand for produce, other suppliers preferred.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Environmental Impacts, e.g. energy intensive production, soil/water quality, biodiversity, land use change, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Legislative issues, e.g. Govt policy decisions, EU CAP, International standards, Environmental law, restrictions on land use, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>
Perceptual Challenges, e.g. Negative Local Opinion, Environmental/Visual Challenges, increased transport, etc.	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>	<input type="radio"/>

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Example of financial model created for plant A

Medium Return	INVESTMENT						REVENUE								
	Year	Elec	Heat	Labour	Financial	Tot	DF	Tot Discounted	Cumulative Discounted	Elec	Heat	Fert	Tot	DF	Tot Discounted
	1	£408	£615	£8,152	£14,432	£23,607	1.05	£22,483	£22,483	0	£1,012	£2,939	£3,950	1.05	£3,762
	2	£408	£615	£8,152	£14,432	£23,607	1.05	£21,413	£43,896	0	£1,012	£2,939	£3,950	1.05	£3,583
	3	£408	£615	£8,152	£14,432	£23,607	1.05	£20,393	£64,289	0	£1,012	£2,939	£3,950	1.05	£10,758
	4	£408	£615	£8,152	£14,432	£23,607	1.05	£19,422	£83,710	0	£1,012	£2,939	£3,950	1.05	£14,008
	5	£408	£615	£8,152	£14,432	£23,607	1.05	£18,497	£102,207	0	£1,012	£2,939	£3,950	1.05	£17,103
	6	£408	£615	£8,152	£14,432	£23,607	1.05	£17,616	£119,823	0	£1,012	£2,939	£3,950	1.05	£2,948
	7	£408	£615	£8,152	£14,432	£23,607	1.05	£16,777	£136,601	0	£1,012	£2,939	£3,950	1.05	£22,858
	8	£408	£615	£8,152	£14,432	£23,607	1.05	£15,978	£152,579	0	£1,012	£2,939	£3,950	1.05	£25,532
	9	£408	£615	£8,152	£14,432	£23,607	1.05	£15,217	£167,797	0	£1,012	£2,939	£3,950	1.05	£28,078
	10	£408	£615	£8,152	£14,432	£23,607	1.05	£14,493	£182,289	0	£1,012	£2,939	£3,950	1.05	£2,425
	11	£408	£615	£8,152	£14,432	£23,607	1.05	£13,803	£196,092	0	£1,012	£2,939	£3,950	1.05	£32,813
	12	£408	£615	£8,152	£14,432	£23,607	1.05	£13,145	£209,238	0	£1,012	£2,939	£3,950	1.05	£35,013
	13	£408	£615	£8,152	£14,432	£23,607	1.05	£12,519	£221,757	0	£1,012	£2,939	£3,950	1.05	£37,108
	14	£408	£615	£8,152	£14,432	£23,607	1.05	£11,923	£233,680	0	£1,012	£2,939	£3,950	1.05	£39,103
	15	£408	£615	£8,152	£14,432	£23,607	1.05	£11,356	£245,036	0	£1,012	£2,939	£3,950	1.05	£41,003
	16	£408	£615	£8,152	£14,432	£23,607	1.05	£10,815	£255,851	0	£1,012	£2,939	£3,950	1.05	£42,813
	17	£408	£615	£8,152	£14,432	£23,607	1.05	£10,300	£266,150	0	£1,012	£2,939	£3,950	1.05	£44,536
	18	£408	£615	£8,152	£14,432	£23,607	1.05	£9,809	£275,960	0	£1,012	£2,939	£3,950	1.05	£46,178
	19	£408	£615	£8,152	£14,432	£23,607	1.05	£9,342	£285,302	0	£1,012	£2,939	£3,950	1.05	£47,741
	20	£408	£615	£8,152	£14,432	£23,607	1.05	£8,897	£294,199	0	£1,012	£2,939	£3,950	1.05	£49,230
	Total PV costs	694,199						£294,199							
	NPV	-644,969													
	Benefit-cost ratio	0.070916													